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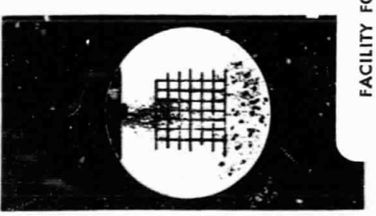
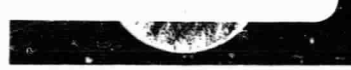
PHASE I INTERIM REPORT

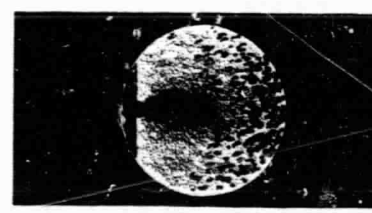
PRODUCING HOLOGRAMS OF REACTING SPRAYS IN LIQUID PROPELLANT ROCKET ENGINES

R. F. WUERKER

B. J. MATTHEWS







PREPARED FOR
JET PROPULSION LABORATORY
PASADENA, CALIFORNIA

BY

TRW
SYSTEMS GROUP
ONE SPACE PARK · REDONDO BEACH, CALIFORNIA

TRW Report No.
68.4712.2-017
Contract 952023

Phase I Interim Report

PRODUCING HOLOGRAMS OF REACTING SPRAYS

in

LIQUID PROPELLANT ROCKET ENGINES

R. F. Wuerker

B. J. Matthews

Prepared for

California Institute of Technology
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FOREWORD

This Phase I Interim Report was prepared for the California Institute of Technology, Jet Propulsion Laboratory, Pasadena, California. The report was prepared by the Power Systems Division of TRW Systems Group, TRW, Inc., and is submitted in accordance with the provisions of JPL Contract 952023.

The Phase I effort was conducted during the period of 1 August 1967 through 7 February 1968. Technical aspects of the contract were administered by Mr. R. S. Rogero, Senior Research Engineer for the Jet Propulsion Laboratory. The Chemical Propulsion Technology Department of TRW Systems' Power Systems Division was responsible for implementing the contract. The Program Manager is Mr. B. J. Matthews. Drs. R. F. Wuerker and L. O. Heflinger of TRW's Physical Electronics Laboratory developed the pulsed laser holography technology and directed the holographic test activities.

Mr. C. A. Anderson and Mr. R. J. Chouinard of the Physical Electronics Laboratory of TRW Systems provided valuable assistance in the design, fabrication and assembly of the holocamera. Major technical contributions were made by Mr. R. A. Briones during the Phase I test operations. The authors wish to acknowledge the support of the Northrop Corporation staff at the JPL/Edwards Test Station at Edwards Air Force Base, California, and in particular, that of Mr. John Short, the test conductor, assisted by Messrs. Robert McKeon, Charles Mayfield, Thomas Egan, and William Tibbitts.

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1. INTRODUCTION

An experimental program to demonstrate the feasibility of producing pulsed ruby laser holograms of reacting sprays was initiated in August 1967. This program, sponsored by the Jet Propulsion Laboratory of the California Institute of Technology, consists of three independent phases of work.

Phase I, completed in February 1968, was directed toward producing holograms of open flame combustion generated by a single unlike doublet injector element. This work resulted in the design of a unique two-beam, laser illuminated holocamera which was constructed and successfully demonstrated. The first holograms ever produced of reacting liquid propellant sprays were recorded with this holocamera during open flame test firings conducted at the Jet Propulsion Laboratory's Edwards Test Station (JPL - ETS).

The second phase of the experimental program will involve holographic studies of combustion phenomena in a three-inch diameter acrylic combustion chamber. A single element doublet injector operating with hypergolic propellants will again be used. Holograms of the combustion process in an 18-inch-diameter rocket engine will be made during Phase III. These studies will use a multi-element impinging stream injector and windowed combustion chamber.

The work accomplished during Phase I is presented in this report. Included in the scope of the report is a description of the design and development of the holographic test apparatus as well as a presentation of the cold flow and open flame test holograms. In addition to the holograms recorded during Phase I, laser illuminated photographic experiments were conducted. The results of these tests are described and representative photographs presented.

2. SUMMARY OF TEST RESULTS

The holocamera test apparatus was delivered to the JPL-ETS in November, 1967, and installed on Test Stand "B". Water flow tests commenced on 30 November and concluded on 6 December 1967. During this period, 24 tests were run in which both holograms and laser illuminated photographs were recorded.

These water flow experiments served as a functional checkout of the holocamera system and provided an opportunity to integrate the camera shuttering and laser output with the rocket test sequence of events. In addition, the water flow spray patterns recorded on the holograms and laser illuminated photographs permit comparative observations to be made with the subsequent open flame test results.

At the conclusion of the cold flow test program, a total of 14 holograms and 10 laser illuminated photographs had been attempted. The majority of these recordings were successful in that droplet distribution could be observed in detail.

The open flame portion of the test program began on 21 December 1967 and was completed 7 February 1968. During this period, 49 hologram recordings were made. Two laser illuminated photographs were also attempted; however, equipment malfunctions resulted in the loss of the photographic record in each instance.

Holographic studies were made of two propellant combinations operating at both ambient and elevated temperatures. The propellant combinations were: 1) Nitrogen Tetroxide (N_2O_4) and a 50 percent (by weight) blend of Hydrazine and Unsymetrical Dimethylhydrazine (50/50 N_2H_4 - UDMH), and 2) Fuming Nitric Acid (FNA) and Unsymetrical Dimethylhydrazine (UDMH).

The open flame tests using N_2O_4 and 50/50 N_2H_4 - UDMH were conducted at ambient propellant temperatures ranging from 46 to 58°F. With the use of propellant conditioning equipment, another series of test firings was made wherein the propellants were conditioned to elevated temperatures of from 81 to 98°F prior to firing. In addition, holograms were recorded of single propellant stream flow (both oxidizer and fuel) from the test injector orifices. A summary of the number and type of recordings in each general category follows:

N_2O_4 - 50/50 Open Flame Tests	Holograms	Photographs
Ambient Prop. Temp. Tests	21	1
Elevated Prop. Temp. Tests	4	1
Single Oxid. Stream Flow	3	-
Single Fuel Stream Flow	2	-
Totals	30	2

Further open flame testing was accomplished using the FNA-UDMH propellant combination. A summary of these tests is listed below. Propellant ambient temperatures varied between 35 and 64°F during these tests. With the propellant temperature conditioning equipment in use, elevated propellant temperatures ranged between 94 and 100°F.

FNA - UDMH Open Flame Tests	Holograms	Photographs
Ambient Prop. Temp. Tests	13	-
Elevated Prop. Temp. Tests	4	-
Single Oxid. Stream Flow	2	-
Totals	19	0

Holographic recordings were made from two different viewing stations with respect to the reacting sprays. For the majority of the open flame tests, the reactants were viewed in the region of stream impingement. From this vantage point, it was possible to record the droplet spray pattern from the injector face to a point approximately 7 inches downstream. In addition, several recordings were made of the droplet dispersion at a viewing station about 12 inches downstream of the injector face.

From the viewing station at the impingement point, three different viewing angles were used. In a predominate number of tests, the major axis of the resultant spray fan (fan plane) was observed. Additional tests were run, however, where the viewing angle was that of the minor axis (or edge view) of the resultant spray fan. And finally, a few oblique viewing angles of the spray fan were recorded.

In general, those holograms made at the impingement station of the fan plane and fan edge resulted in the best quality recordings. Holograms made of the downstream droplet dispersion failed to reveal much information. It is not known whether the lack of droplet dispersion detail in the downstream region was due to limited quality of the holograms or simply the nonexistence of liquid droplets at this distance from the injector face.

3. TEST APPARATUS

3.1 HOLOCAMERA DESIGN

To produce successful holograms of reacting sprays in both an unconfined state, and later in the restricted environment of rocket combustors, a new holocamera of improved qualities had to be designed and constructed. In evolving this system, several operational factors had to be considered. In essence, the holocamera design would have to:

- Accommodate and record the unconfined combustion of a single impinging stream injector element, as well as the combustion phenomena within windowed chambers of 3-inch and 18-inch diameters.

- Survive the vibrational loads, thermal environment and corrosive atmosphere encountered in typical rocket test stand operations with earth storable propellants.

- Withstand prolonged exposure to varying weather conditions, since the rocket test stand would not be enclosed or sheltered.

- Be operated from a console in a blockhouse 500 feet from the rocket test stand.

- Operate from a "sequence timer" which automatically programmed the events in each experiment.

- Make provisions for optical alignment and adjustment as well as general maintenance and parts replacement in the field.

The holocamera design which was ultimately formulated to meet the varied requirements of recording combustion phenomena is shown schematically in Figure 3-1. This design is an improved version of a much smaller unit which has been in use at the Physical Electronics Laboratory of TRW Systems.* The design philosophy behind the new and larger holocamera is the same as that which was worked out for the earlier unit. Major changes, however, were incorporated which upgrade the overall performance and make the holography technique applicable to 14-inch diameter scenes (limited only by the diameter of the focusing lens), and scenes 2 times the focal distance of the lens system. In the present holocamera design, this distance is 1 meter.

*R. E. Brooks, et al., "Pulsed Laser Holograms," IEEE Journal of Quantum Electronics, Vol. QE-2, p. 275, August, 1966.

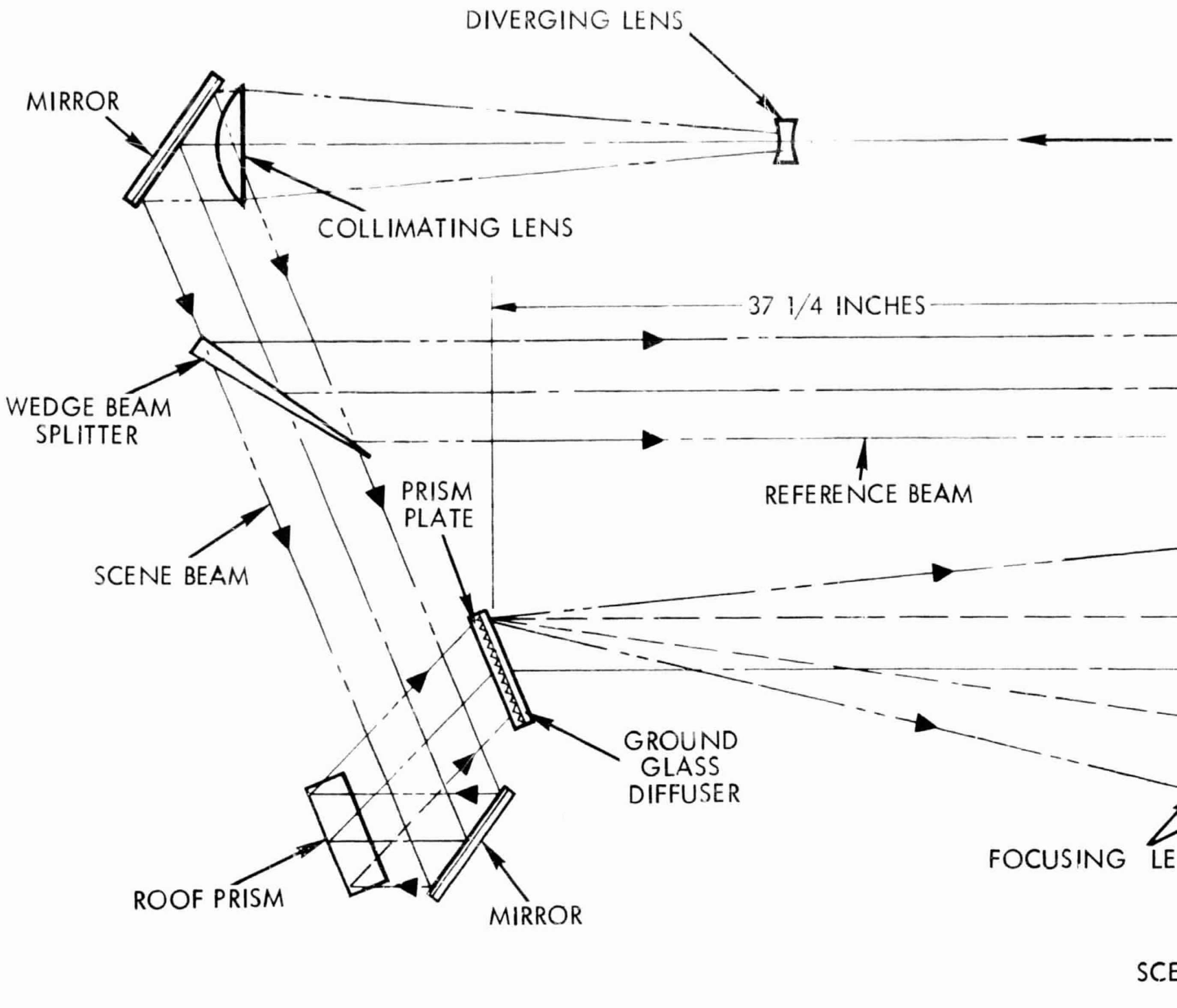

Fig 3-1.A

6-A

FOLDOUT FRAME

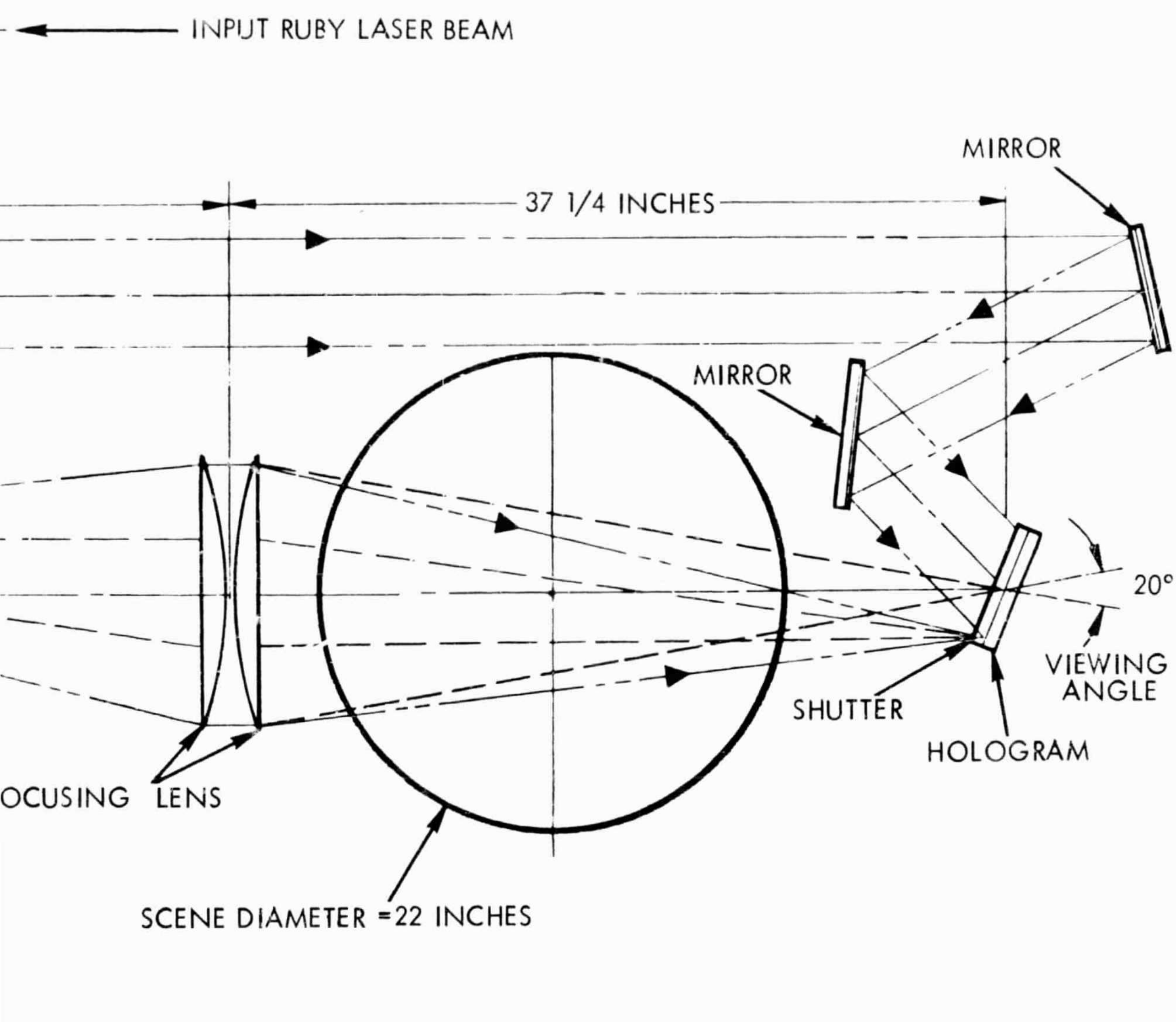

Figure 3-1.B Schematic diagram of TRW focused ground glass transmission holocamera design for producing reacting spray holograms

FOLDOUT FRAME

Basically, the holocamera has two spacially and temporally matched scene and reference beams. Spacial matching is achieved by proper use of reflectors, a roof prism, and a large pair of condensing lenses. The latter pair of elements takes the light scattered by a ground glass screen and focuses it back onto the hologram. The mirrors and the roof prism insure that each scene ray combines once again with the equivalent reference ray at the plane of the hologram. Temporal matching is achieved by arranging the distances of the mirrors so that after division by the beam splitter, both scene and reference beams travel over the same optical path lengths; the accuracy of the path match is within the temporal coherence limits of the laser illuminator.

Examining the schematic of Figure 3-1 in more detail shows that the beam from the laser is first expanded by a Galilean telescope to a diameter of approximately 5 inches. It is then deflected by a mirror and directed onto a wedge beam splitter. The beam splitter divides the original laser beam into two beams: a horizontally propagating reference beam and a direct beam which propagates at approximately 22 degrees with respect to the vertical. The angle of the wedge is chosen so that the beam reflected from the back surface misses the far mirror, upon which the reference beam (from the front surface) is incident.

The reference beam, after traversing the full length of the holocamera, strikes a mirror which deflects it at approximately 40 degrees relative to the horizontal onto a second mirror. The second mirror then deflects the reference beam into the hologram. The mirror is set so that the reference beam and axis of the condensing lens system are at 45 degrees in respect to one another.

The scene beam, after emerging from the far side of the wedge beam splitter, is incident upon a front surface mirror set at approximately 60 degrees relative to the horizontal. This mirror reflects the light into a roof prism which inverts the beam and directs it onto the "prism plate", set also at an angle of 45 degrees relative to the axis of the condensing lens system. This prismatically-cut plate bends the scene light into the horizontal direction onto a frosted glass plate, which scatters the light into the forward direction into the condensing lens system. As noted earlier, the condensing lenses refocus the light (at a 1 to 1 image magnification) onto the hologram. Both the prism plate and the ground glass are canted at 67-1/2 degrees relative to the axis of the condensing lenses.

The hologram itself is a 4 x 5 inch glass photographic plate oriented at 67-1/2 degrees. This angle was chosen so that the normal to the photographic plate bisects the angle between the direction of the reference beam and the axis of the condensing lens system. As a result, the interference pattern between scene and reference beam is perpendicular to the emulsion. Holograms made in this manner are believed to be freer of distortion than those wherein the "blazing" is not perpendicular to the plate.

Since the hologram itself is tilted, the ground glass screen must also be tilted, but in the opposite direction, to insure that the optical path length between the ground glass screen and the hologram is everywhere the same.

The 4 x 5 inch photographic plate is mounted in a standard photographic plate holder, which is inserted behind a focal plane shutter taken from a Graflex camera. The focal plane shutter is a "window shade" shutter arrangement which spans a 4 x 5 inch plate. It was modified for solenoid operation.* A Wratten No. 70 gelatin filter is mounted before the plate to protect it against exposure by the background light, as well as the light generated by the combustion. These filters have a transmission of approximately 75 percent at the 0.694 micron ruby wavelength, and a transmission of 63 percent at 0.65 micron, while at shorter wavelengths (into the visible), the filters are essentially opaque.

In addition to the "window shade" focal plane shutter previously described, a second mechanical shutter was installed. This shutter, termed a "capping shutter", is mounted externally to the viewing window leading to the focal plane shutter and film plate. The capping shutter is solenoid operated and is opened via the sequence timer approximately 0.2 seconds before the laser is fired. This shutter eliminated the ambient daylight

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*Later in the program, the stop action was removed, thus keeping the 4 x 5 inch open frame in continuous motion. This cut the ambient exposure of the film by ~ 1/20, but also made tearing of the cloth shutter more probable.

which leaked through the window shade shutter and caused the film to fog. This modification was particularly important for the hot firing tests. During these tests, the dark slide on the film cassette was pulled before all personnel departed the test stand area for the firing. The slide was not replaced until after the test had taken place and the area cleared for personnel to return to the test stand. Typically, this time interval was in the order of twenty minutes. This was a sufficient amount of elapsed time to allow the film to fog if the day was bright and clear.

As can be seen from the schematic diagram of Figure 3-1, the reference beam of the holocamera is parallel to the scene beam. This design approach was selected because it eliminates the uncertainties related to the reference beam to be used in reconstructing the hologram. Further, it makes possible the projection of real images (from the hologram) which can then be examined by a high-resolution, short working distance optical microscope. An additional feature of the holocamera design is the ability to replace the condenser lens array by one of shorter focal length, thereby increasing the angular field of the recorded scene at the expense of depth.

In summary, the holocamera design shown schematically in Figure 3-1 is sufficiently versatile to accommodate the physical requirements of all three phases of the test program. The holocamera has the following significant features:

- The scene and reference beams are spacially and temporally matched.
- Without any modification, the holocamera will accept windowed combustion chambers up to 26 inches in diameter.
- Holographic recordings are made on a 4 x 5 inch photographic plate with an angular field, which fills both eyes simultaneously so that reconstruction will appear three dimensional to the viewer.
- The reference beam is parallel, thereby minimizing errors in reconstruction and facilitating easy reconstruction of a real image.
- The photographic plate is symmetric with respect to the scene and reference beam propagation angle. This is thought to minimize distortion of the reconstruction, since the recorded interference patterns are perpendicular to the plane of the photographic emulsion.

3.2 RUBY LASER

The laser illuminator and power supply furnished by TRW was in existence prior to the initiation of the contract. The power supply required further modification so that it could be remotely operated and monitored from the main console, located in the JPL-ETS control blockhouse. Provisions had to be made for remote manual operation as well as automatic and properly sequenced operation during a test firing.

The illuminator used for this program is conventional Kerr cell, Q-switched ruby laser consisting of a 99 percent dielectric end reflector, a nitrobenzene Kerr cell, a Glan Polarizing prism, an adjustable intercavity aperture, a 1/2-inch diameter x 3-3/4-inch long ruby laser rod, and a sapphire resonate end reflector. All of these components are mounted upon an optical rail machined from an aluminum I-beam.

Modifications to the laser illuminator were minor in nature. Because of the corrosive atmosphere generated by the propellant vapors during a test firing, the laser was enclosed in a galvanized steel shroud (discussed in the next section). Mounting provisions were also required for the alignment autocollimator and gas laser.

3.3 HOLOCAMERA CONSTRUCTION

The holocamera design shown in Figure 3-1 lends itself to a simple and rugged method of mounting. The basic cross-member of the structure is a 6-inch diameter x .125-inch wall aluminum pipe. This pipe surrounds the reference beam of the holocamera. On each end of this aluminum pipe are suspended sheet aluminum housings in which the mirrors, shutter and plate holder, beam splitter, etc., are mounted. In addition, this member is used to suspend the 15-inch diameter focusing lenses. These lenses are mounted in an aluminum collar which is attached to the 6-inch diameter pipe and held in place with clamps.

Figure 3-2 shows an assembly drawing of the holocamera and laser. It may be seen that the 6-inch diameter pipe becomes in effect a large inverted optical rail. On one end is hung an aluminum housing containing the reference beam mirrors, photographic plate holder and shutter mechanism. At the opposite end, another aluminum housing contains the mirrors, roof prism and wedge beam splitter of the scene beam. All optical components are

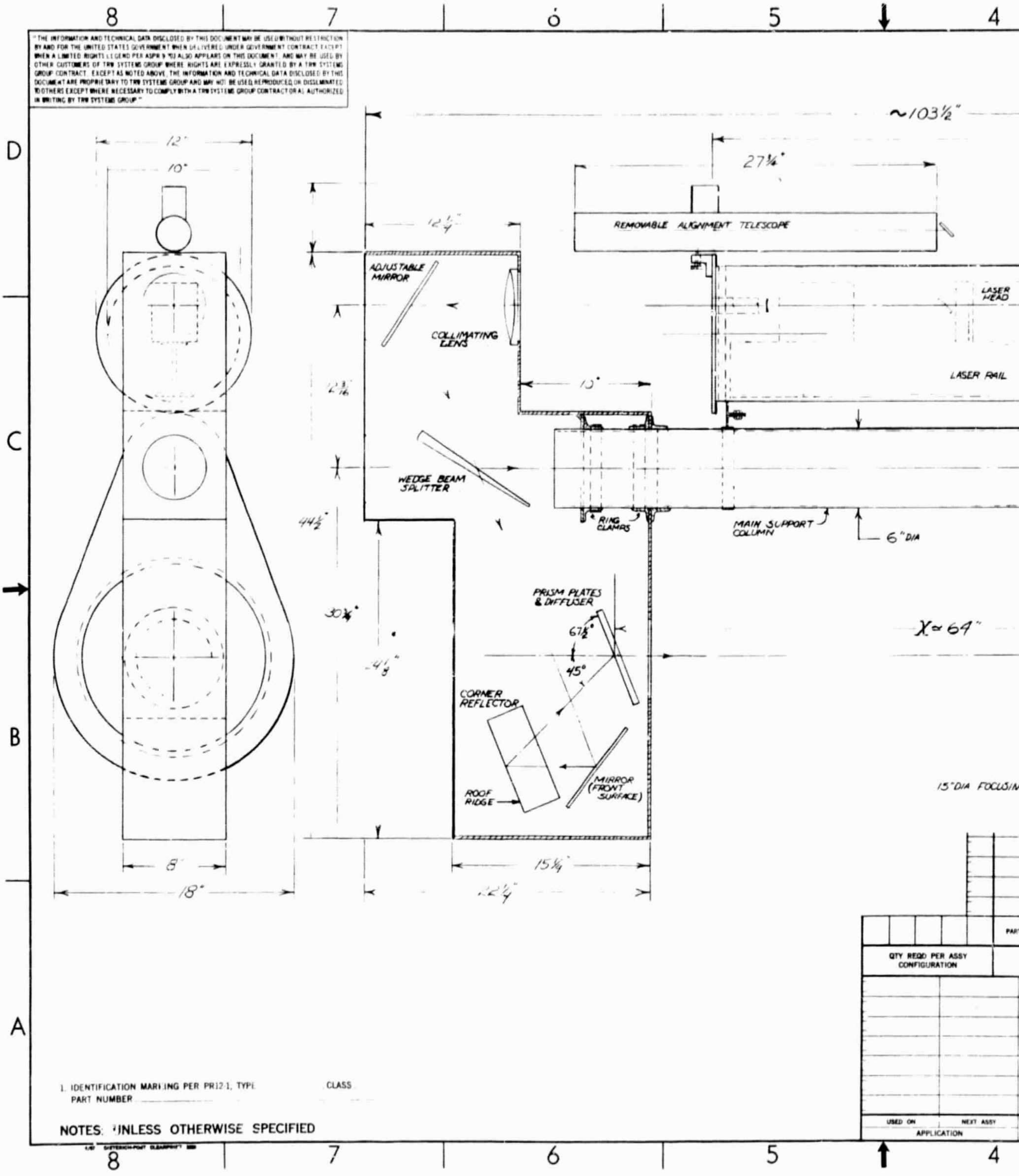

Fig 3-2.A

11-A

FOLDOUT FRAME

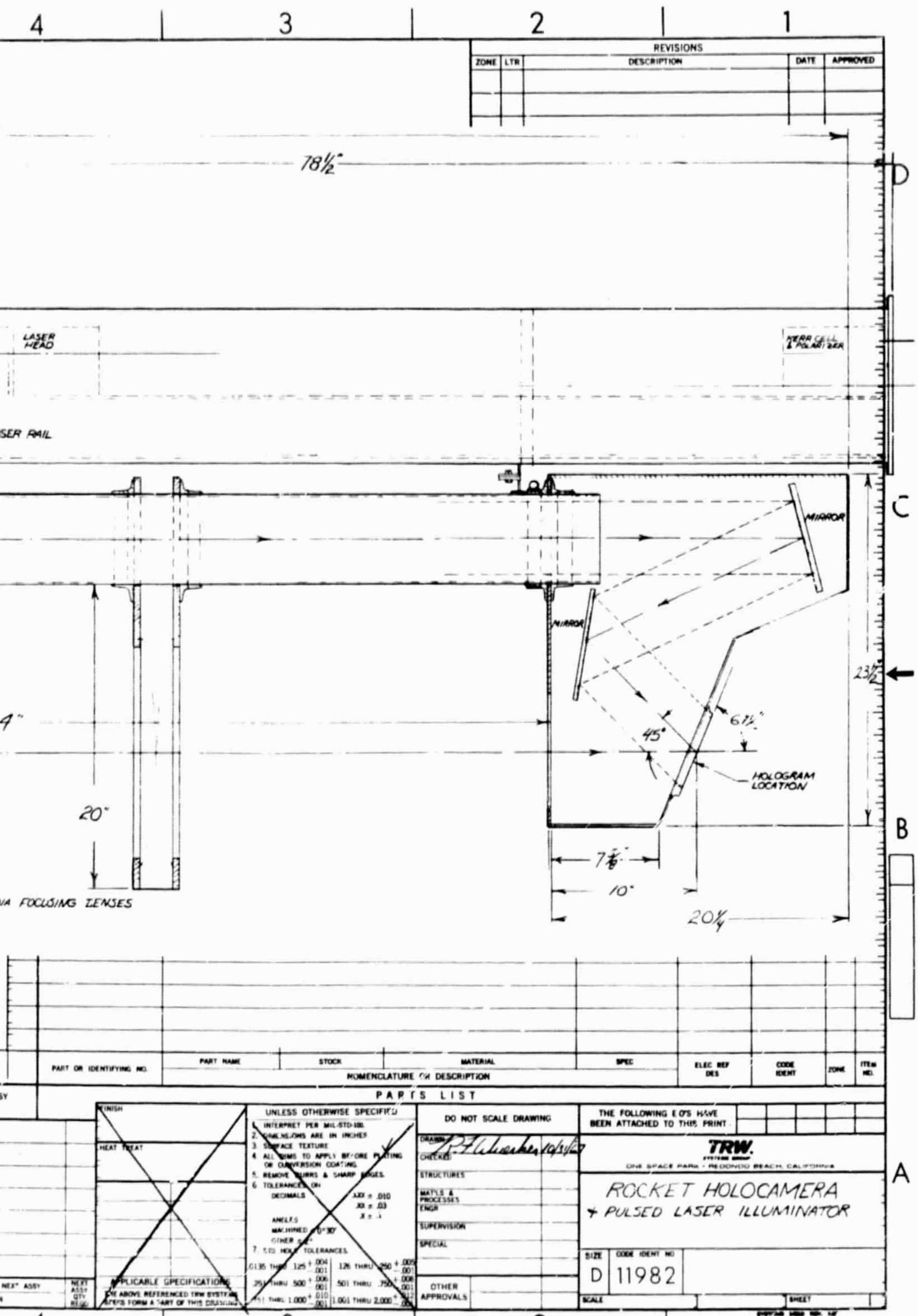

Figure 3-2.5 Holocamera and laser illuminator assembly drawing

FOLDOUT FRAME

precision mounted so that their orientation may be adjusted as required for optical path alighment. In addition, provisions for vibration and shock resistance have been incorporated.

This type of construction allows the holocamera to be mounted in a trunion, thus making it possible to rotate the plane of the holocamera parallel to the mounting plates of the injector test element, as it is mounted on the existing JPL rocket test stand. The ability to rotate the holocamera about the axis of the reference beam will also minimize the contact of the elements of the holocamera with the products of combustion, particularly during the open flame tests.

The photographs of Figures 3-3 through 3-5 further illustrate the holocamera construction. Figure 3-3 is an overall view of the assembled holocamera showing the steel pipe legs used to mount the apparatus in the laboratory. These legs were later modified (at the Edwards Test Site) to position the holocamera at the correct height. To the left is the TRW-constructed power supply used with the pulsed ruby laser. Figure 3-4 shows the details of the beam splitter and mirror installations in the left-hand aluminum housing attached to the reference beam 6-inch diameter pipe. In Figure 3-5 may be seen the mirrors and Graflex shutter assembly. The film plate holder is mounted externally to the aluminum housing.

The laser readily slides in and out of the galvanized steel pipe which was fabricated to protect the optical components of the laser from both the elements as well as from the combustion products. Aluminum end flanges seal off the pipe. The laser beam emerges through windows in the end flanges. The pipe can be pressurized with nitrogen gas (available at the JPL test site) to minimize penetration of foreign elements and propellant fumes into the sensitive surfaces of the laser.

The laser illuminator is positioned above the holocamera which is rigidly mounted to the 6-inch diameter pipe. This arrangement permits a very compact overall design. In addition, it facilitates the maintenance of optical path alignment between the laser and the holocamera optics.

Originally, it was planned to position the laser equipment off to one side of the holocamera approximately 20 feet from the test area. The utilization of a continuous nitrogen purge and the galvanized steel pipe

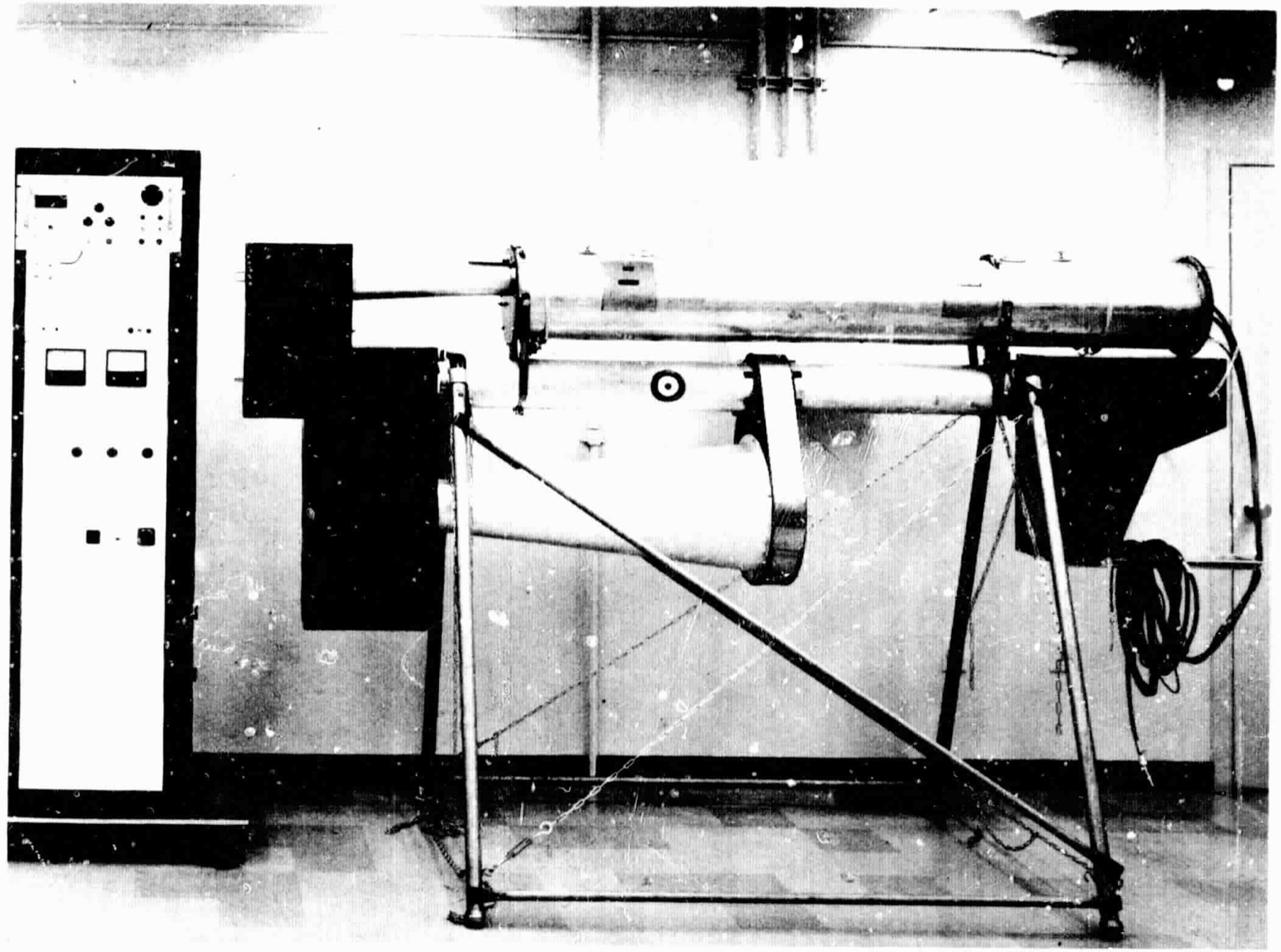

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Figure 3-3. TRW laser illuminated holocamera assembly (The laser power supply cabinet is shown at the left of the photograph.)

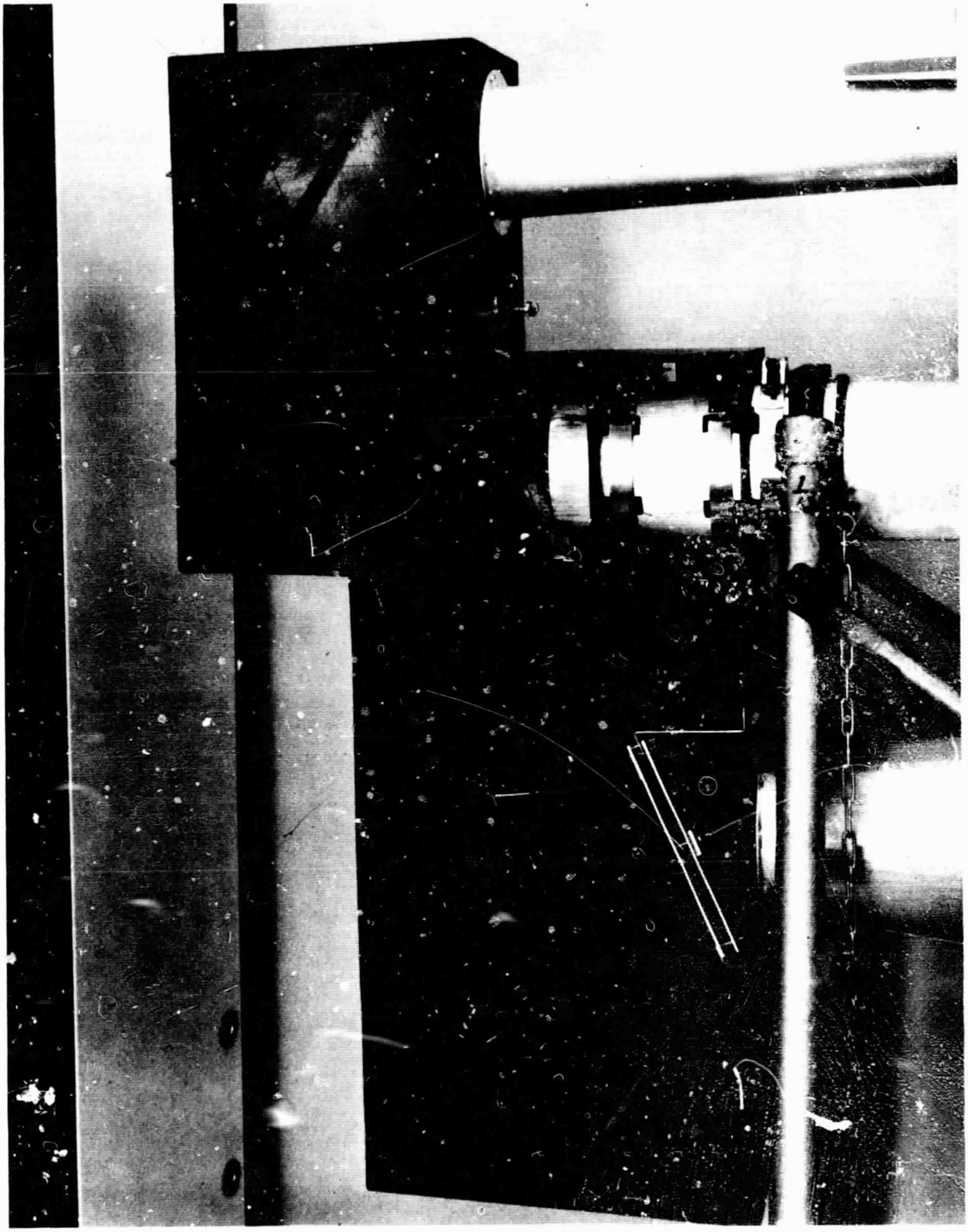

Figure 3-4. Left-hand aluminum housing containing the beam splitter and mirror installations

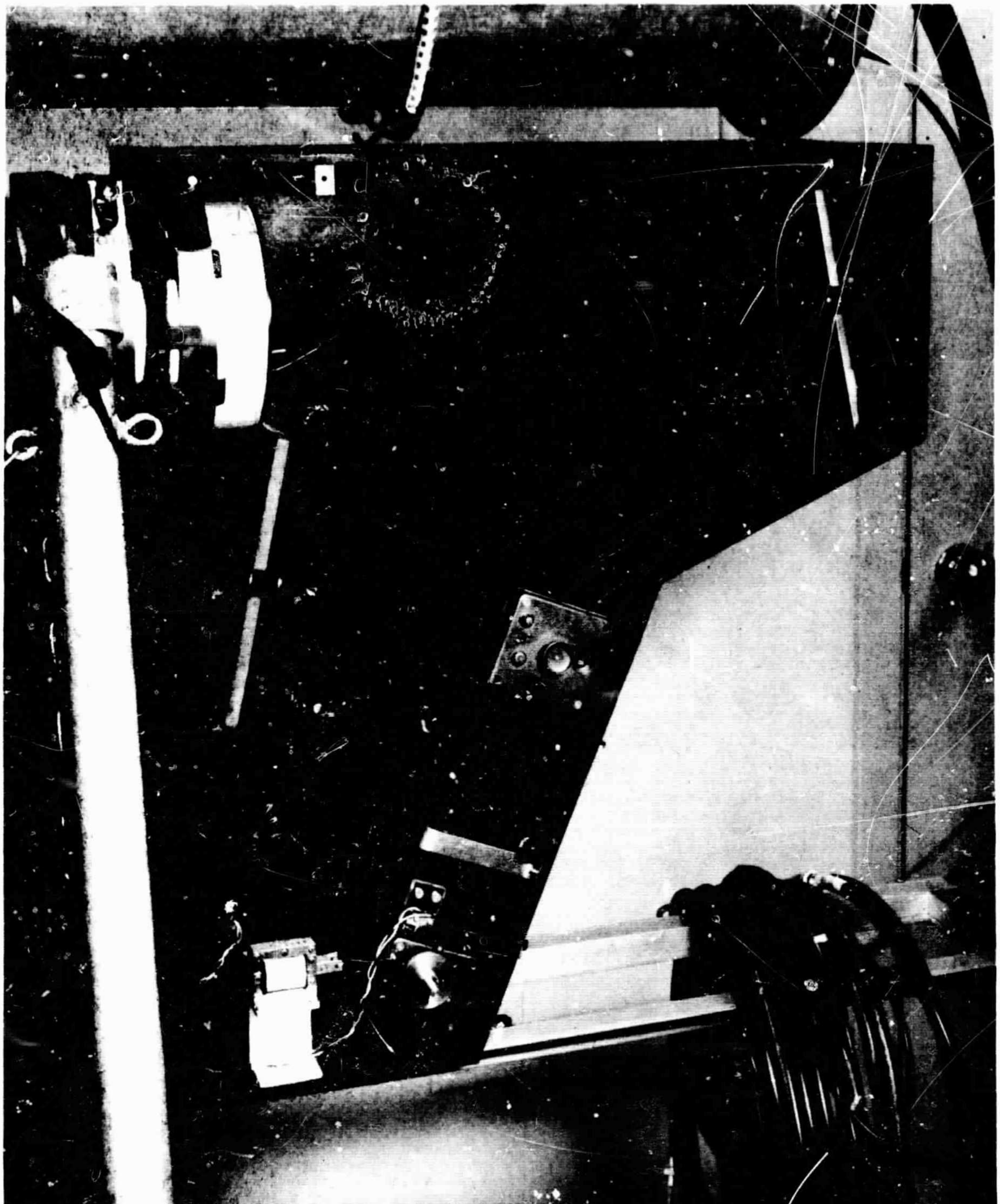

Figure 3-5. Right-hand aluminum housing containing the reference beam mirrors, shutter mechanism and film holder

shroud around the laser were ultimately considered adequate protection, however, and the laser illuminator was mounted in proximity with the holocamera as shown in Figure 3-2.

3.4 HOLOCAMERA INSTALLATION

With the construction of the holocamera completed, static test holograms were made at TRW's Physical Electronics Laboratory to confirm the adequacy of the design. The holocamera and associated equipment were transported to the JPL Edwards Test Station (ETS) and installed at one of the liquid rocket sea level test stands. Installation of the holocamera at the test stand is shown in Figures 3-6 through 3-8. As shown in Figure 3-6, the holocamera was positioned such that it straddled the open flame test injector element. The injector element was located laterally at the approximate center of the holocamera scene volume.

The photographs of Figures 3-7 and 3-8 are left- and right-hand views of the holocamera installed at the rocket test stand. For the open flame tests, a special bracket was provided by JPL to mount the injector element on a capping plate. This plate, in turn, was affixed to the nozzle exit plane of a large rocket engine already in place on the test stand. The mounting bracket for the injector element was adjustable. It could be adjusted longitudinally so that the injector element could be located at any desired viewing position (over a distance of approximately 12 inches) with respect to the holocamera scene volume. As a result, it was possible to view events taking place in the region of stream impingement, or by relocating the injector element, to view the dispersed droplet patterns 12 inches downstream of the injector.

In addition to the longitudinal adjustment, the injector element could also be rotated or attached to the mounting bracket in one of three radial positions. This permitted holographic recordings of: 1) the resulting spray fan major axis (the major axis oriented normal to the holocamera scene beam), 2) the edge view or minor axis of the spray fan, and 3) a 45 degree oblique view of the spray fan.

The power supply for the laser and the regenerative water cooling system for the laser head were positioned approximately 20 feet behind the rocket test stand. These units are shown in Figure 3-9 and 3-10, respectively.

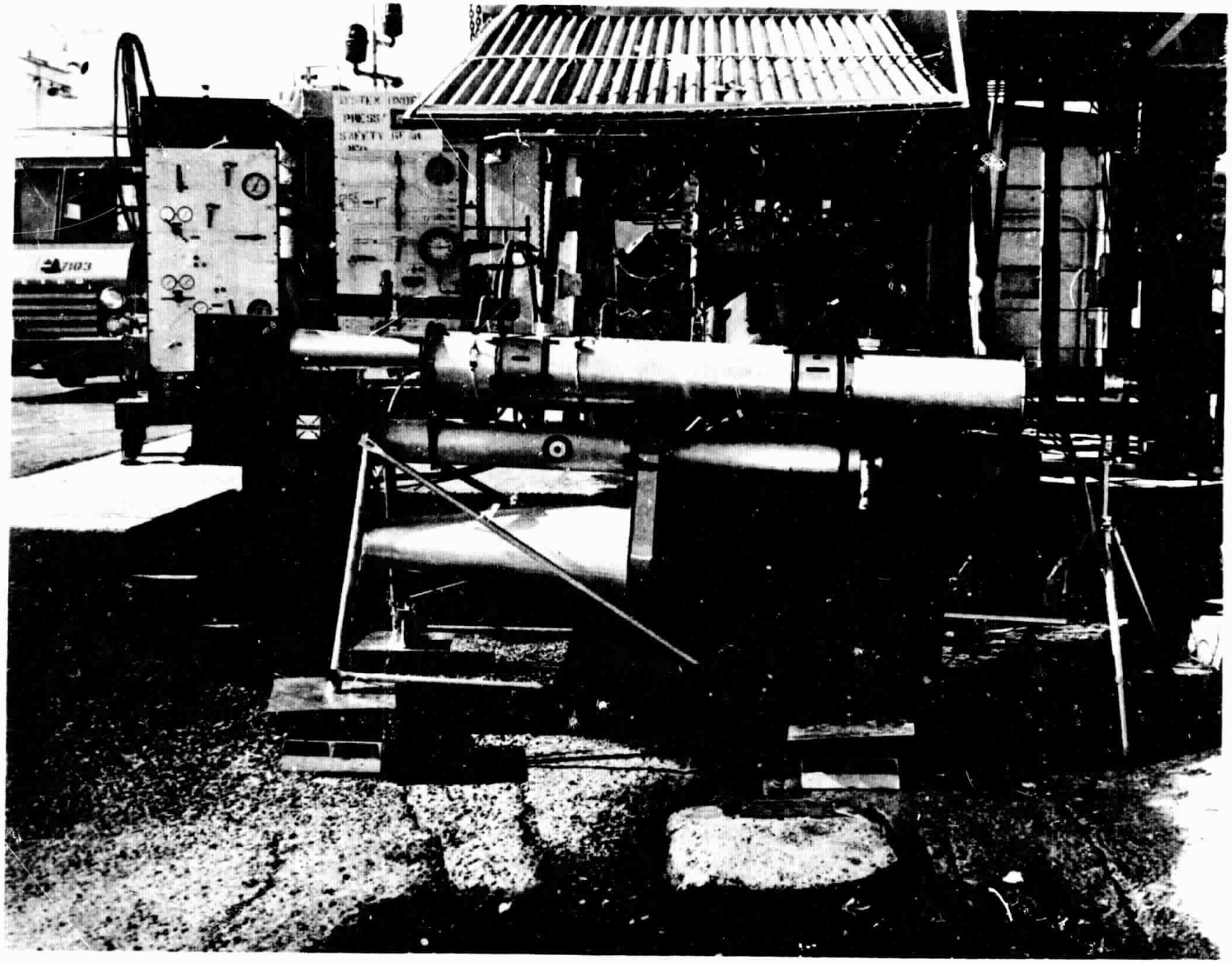

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Figure 3-6. Side elevation photograph of the TRW holocamera installed at the JPL-ETS rocket test stand for open flame testing

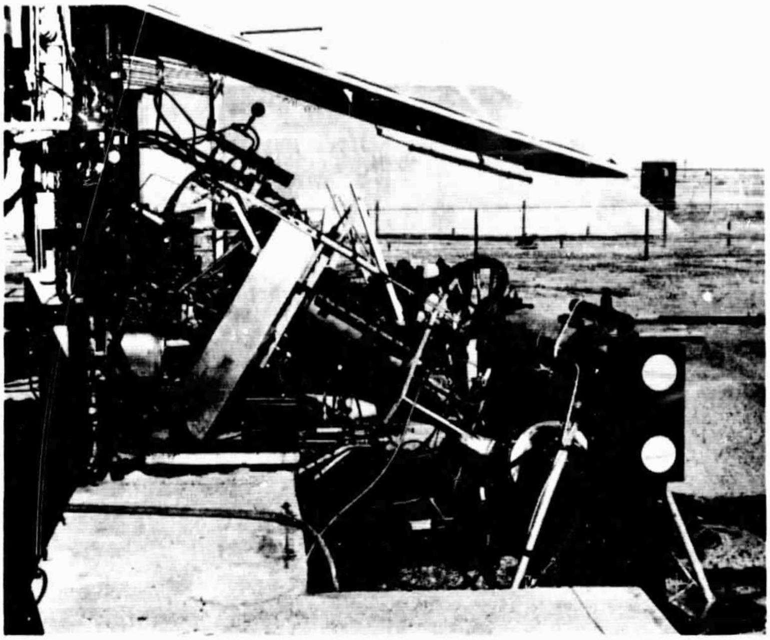

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Figure 3-7. Left side elevation photograph of the holocamera installation at JPL-ETS rocket test stand

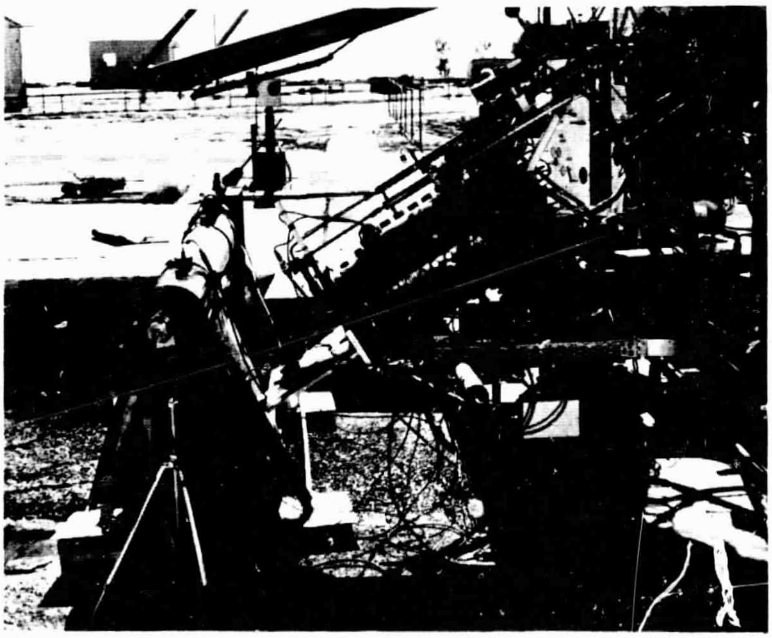

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Figure 3-8. Right side elevation photograph of the holocamera installation at JPL-ETS rocket test stand

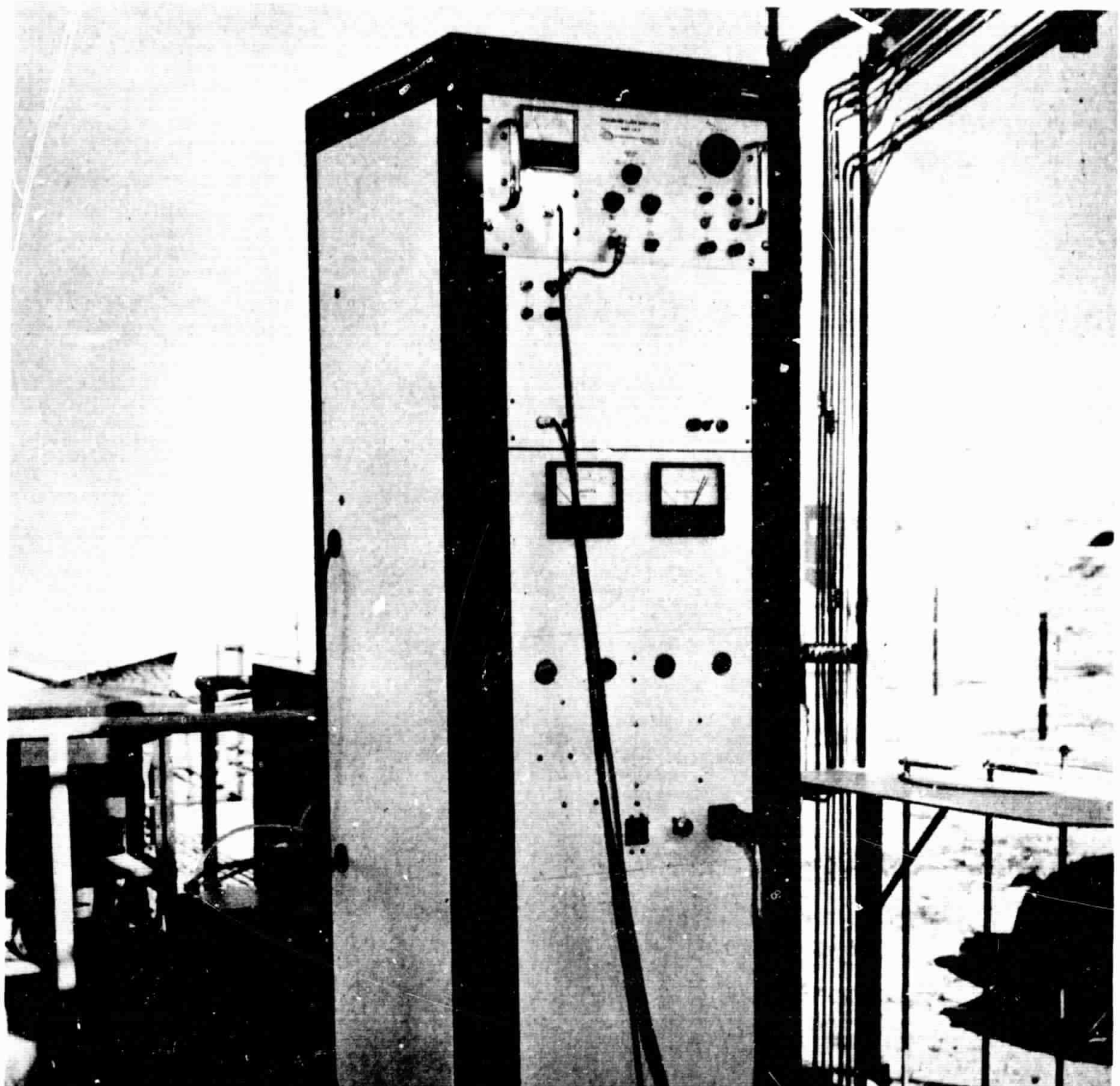

Figure 3-9. TRW power supply unit located at the rocket test stand

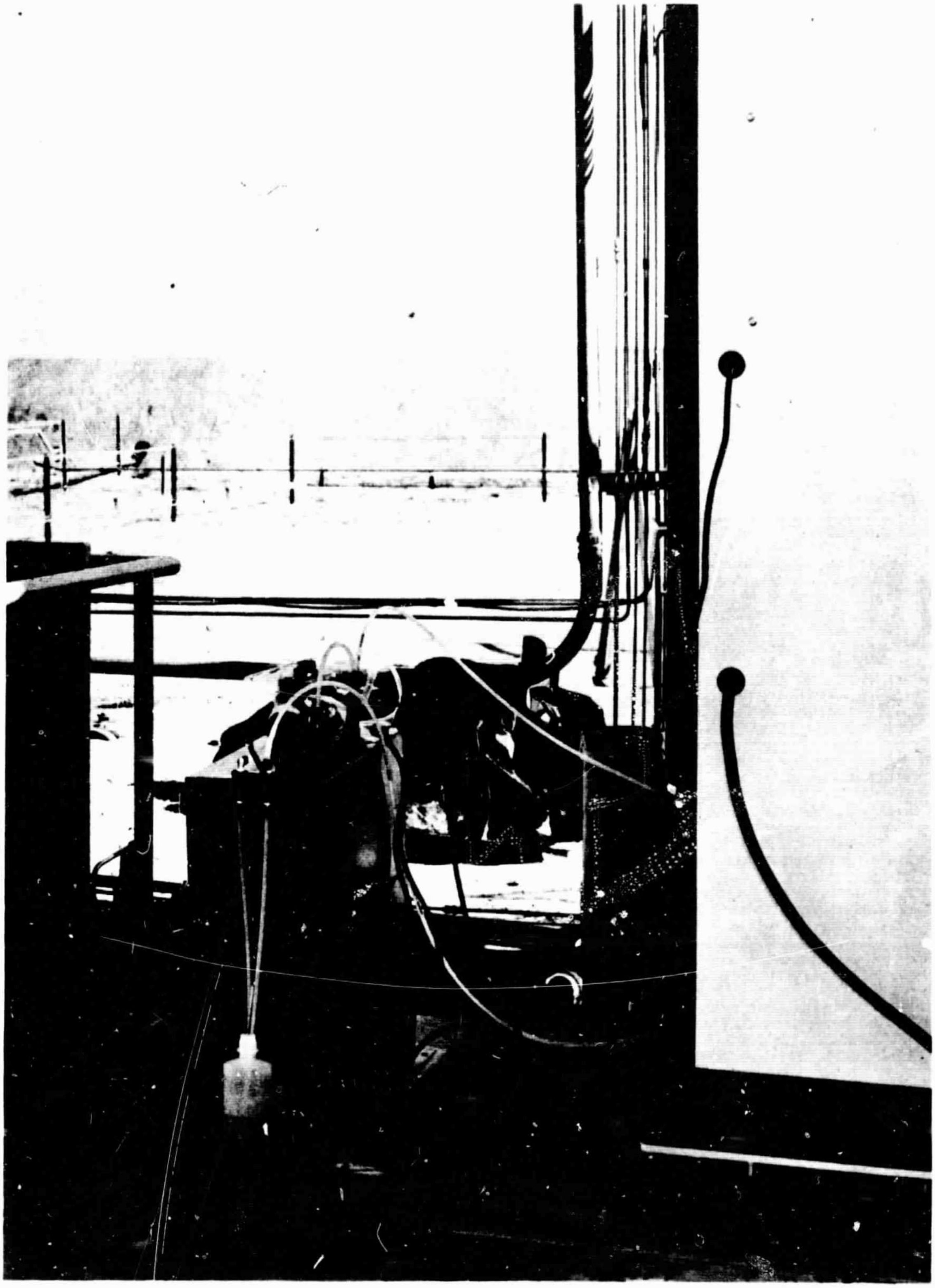

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Figure 3-10. TRW portable cooling system for the laser head

3.5 HOLOCAMERA OPERATION

The following paragraphs provide a description of the operating characteristics and procedures for the pulsed ruby laser holocamera used for the Phase I test program.

The laser power was monitored by a biplanar photodiode which could easily drive the 500 foot length of 50 Ω coaxial cable, between the detector housing and the oscilloscope in the blockhouse. The photodiode was mounted in the housing attached to the end flange which sealed the steel shroud containing the laser illuminator. Light transmitted by the 99 percent dielectric mirror on the end of the laser passed through a plexiglass window and struck several ground glass diffusing screens, as well as a Corning CS 2-64 red filter before being registered by the photodiode. The electrical current pulse (proportional to the laser light intensity) was transmitted by coaxial cable to either a Tektronix 519 high frequency traveling wave oscilloscope (0.3 nanosecond rise time) or to an integrator and a conventional Tektronix Type 545 oscilloscope. The latter measured the relative energy in terms of the charge passed by the photodiode in terms of the voltage across a capacitor. This monitoring was considered most important, since it enables one to know whether the laser emitted a clean single pulse or whether it emitted a series of pulses due to misalignment. The latter resulted in holographic interferograms, rather than the desired single exposed holograms.

The water cooler used to cool the laser head was a part of TRW's inventory. For this program, the cooling system was connected to the laser rod flash lamp housings (within the steel laser shroud) via plastic tubing and bulk head fittings in the end flange. For operation at the desert test site, the circulating water had to be mixed with ethyl alcohol to prevent freezing. The water cooler was located with the laser power supply approximately 20 feet from the test stand.

The ruby laser could be fired either at the power supply unit at the test stand, from the remote control console in the ETS blockhouse, or by the automatically programmed sequence timer. The laser was fired when the focal plane (window shade) shutter was activated. This was accomplished through the use of a microswitch which sensed the open position of the focal plane shutter. In addition, approximately 400 milliseconds prior to activating the focal plane shutter, the solenoid operated capping shutter was opened in the automatic sequence of events.

The integrated laser emission was monitored on an oscilloscope (as previously indicated). The output of the oscilloscope (vertical amplifier output) was also connected to the recording oscillograph used to monitor all of the operating parameters of the injector test element. As a result, the precise time of the hologram recording could be related to the other measured parameters of the test operation.

In order to make holograms, it was necessary only to align the laser and check to see that the holocamera had not been physically moved.* Alignment of the laser was achieved by mounting the dark field autocollimator into position, inserting the periscope into its mounting hole (thereby deactivating the ruby laser trigger), removing the $\lambda/4$ bias from the Kerr cell by adjustment of the mirror alignment screws, and superimposing the light returned from the resonate reflector onto the light observed in the rear mirror. The periscope was then withdrawn, the laser capacitor banks charged, and the laser fired.

The output from the laser was monitored with a photodiode. The operation of the laser was considered satisfactory when an oscillograph sweep consisting of a single step of proper amplitude (approximately 0.6 volts) was recorded.

If the holocamera or the position of the laser illuminator relative to the axis of the holocamera had to be aligned, one then removed the negative diverging lens (just before the output of the ruby laser amplifier) and taped a piece of unexposed and developed Polaroid film before the collimator lens, charged the banks, and fired the laser. The emitted energy marked the film. The small gas laser (Radiation Physics) was placed in its holder, a periscope inserted in the second mounting hole, and the leveling screws adjusted until the gas laser beam passed centrally through the aperture in the ruby laser oscillator and the pulse laser mark in the

*Alignment of the holocamera meant that the scene and reference beams overlapped, and that scene and reference beam optical path lengths were equal.

photographic film. The gas laser beam was thus coincident with the pulse laser beam. The marked film could be removed and the diverging lens re-plased. The cover was removed from the side of the housing on the holo-camera, and the capping and focal plane shutters were opened. An old 4 x 5-inch photographic plate, upon which had been cemented a white paper, was placed in one of the wooden 4 x 5-inch holders and inserted into the mount in the holocamera. One could (after the sun had set) observe the superimposed scene and reference patterns on the paper glued to the plate. A wire cross at the entrance to the holocamera cast a single shadow if the two beams were properly superimposed. Proper (1:1) scene-reference beam intensity ratios were checked by eclipsing the opposite part of either beam and comparing it against the other.

Temporal matching was essentially a laboratory alignment which could be verified by making a hologram in which a large stair-step block of plexiglass was set in the scene beam of the holocamera.

With both the laser illuminator and the holocamera aligned, it was then necessary to check the programming of the laser and shutter functions relative to the firing of the injector. Verification of the proper sequencing of events was done by recording all parameters of interest on a highspeed recording oscillograph "dry" run. When the desired sequencing was achieved, the apparatus was ready to record holograms.

A loaded film cassette was inserted in the holocamera, the focal plane shutter cocked manually, and the dark slide removed. Rocket test safety operations dictated that all personnel clear the immediate area of the test stand. Once the film was loaded in the holocamera, the operation of the equipment was done from the blockhouse instrument room used to conduct the firing. Prior to the actual injector test firing, the laser was pulsed and monitored from the remote control panel in the blockhouse. If the laser emission was satisfactory, the test firing proceeded.

After the test firing was complete and test stand area reopened, the dark slide was reinserted in the cassette, the cassette withdrawn from the camera, and either stored or immediately taken to the "darkroom" for development.

The exposed holograms were developed as soon as possible, particularly since this enabled a check on the test results and to verify the quality and nature of the recorded scene.

3.6 LASER PHOTOGRAPHY

The holocamera was also fitted with brackets so that a bellows-type copy camera could be positioned to make conventional photographs of the flow phenomena. The camera thus used the laser and beam forming optics as a high grade transmission type illuminator. Even the focal plane shutter functioned as the camera lens shutter. The camera was focused and photographs recorded, using the complete sequence already described.

For laser photography only the reference beam was not used. Laser photography was incorporated in the program to serve as a basis for comparison against the holographic recordings. Since it was done as an afterthought, it has not been systematically investigated. The results of this work are presented in Section 4.1 of this report.

3.7 INJECTOR TEST ELEMENT

The injector test element used for the Phase I cold flow and open flame test hologram recordings was furnished by JPL. This element, shown in the photographs of Figures 3-11 and 3-12 consists of two impinging stream orifice tubes mounted in an aluminum block. The included angle of impingement is 45 degrees. The inside diameter of each tube is 0.173 inch. The orifice tube is L/D = 100 to assure fully developed turbulent flow. Orifice pressure drop as a function of water flow rate is presented in Figure 3-13.

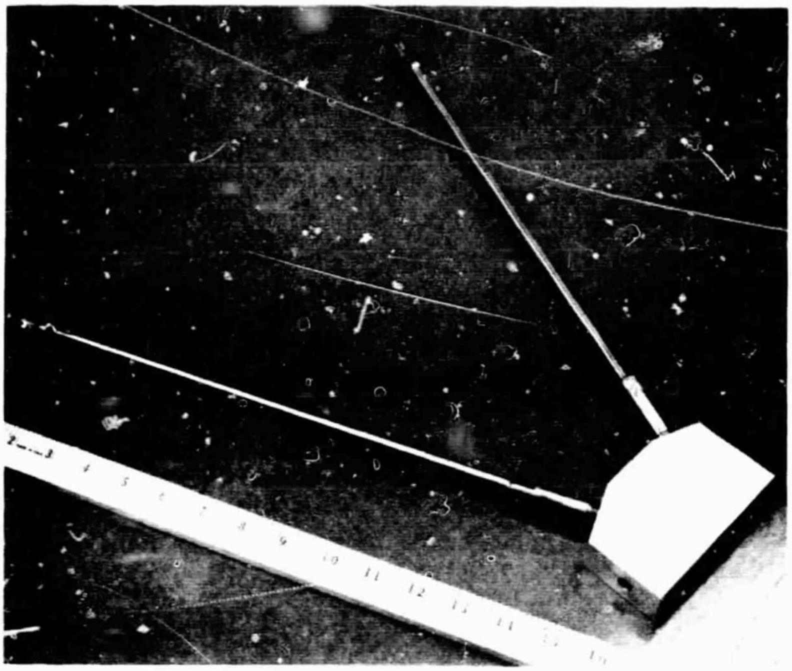

Figure 3-11. Photograph of the JPL single element impinging stream injector used for the Phase I open flame tests

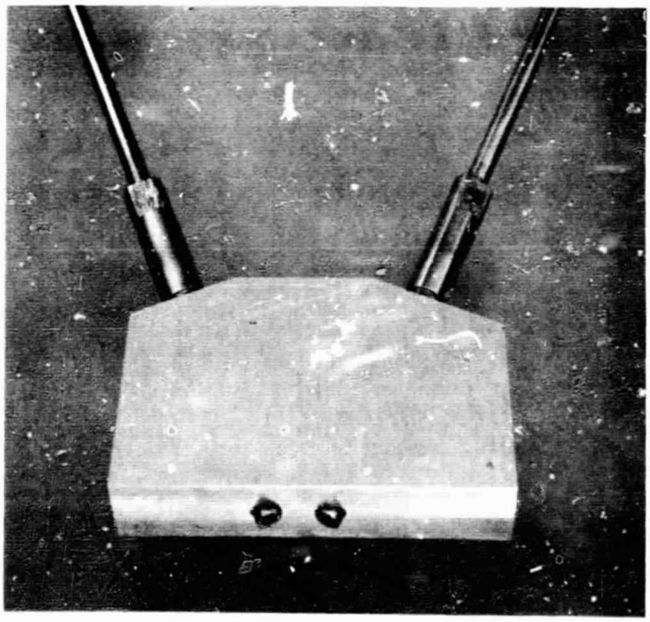

Figure 3-12. Closeup view of the JPL single element injector showing the 0.173 inch diameter tubes extending slightly beyond the face of the aluminum injector block

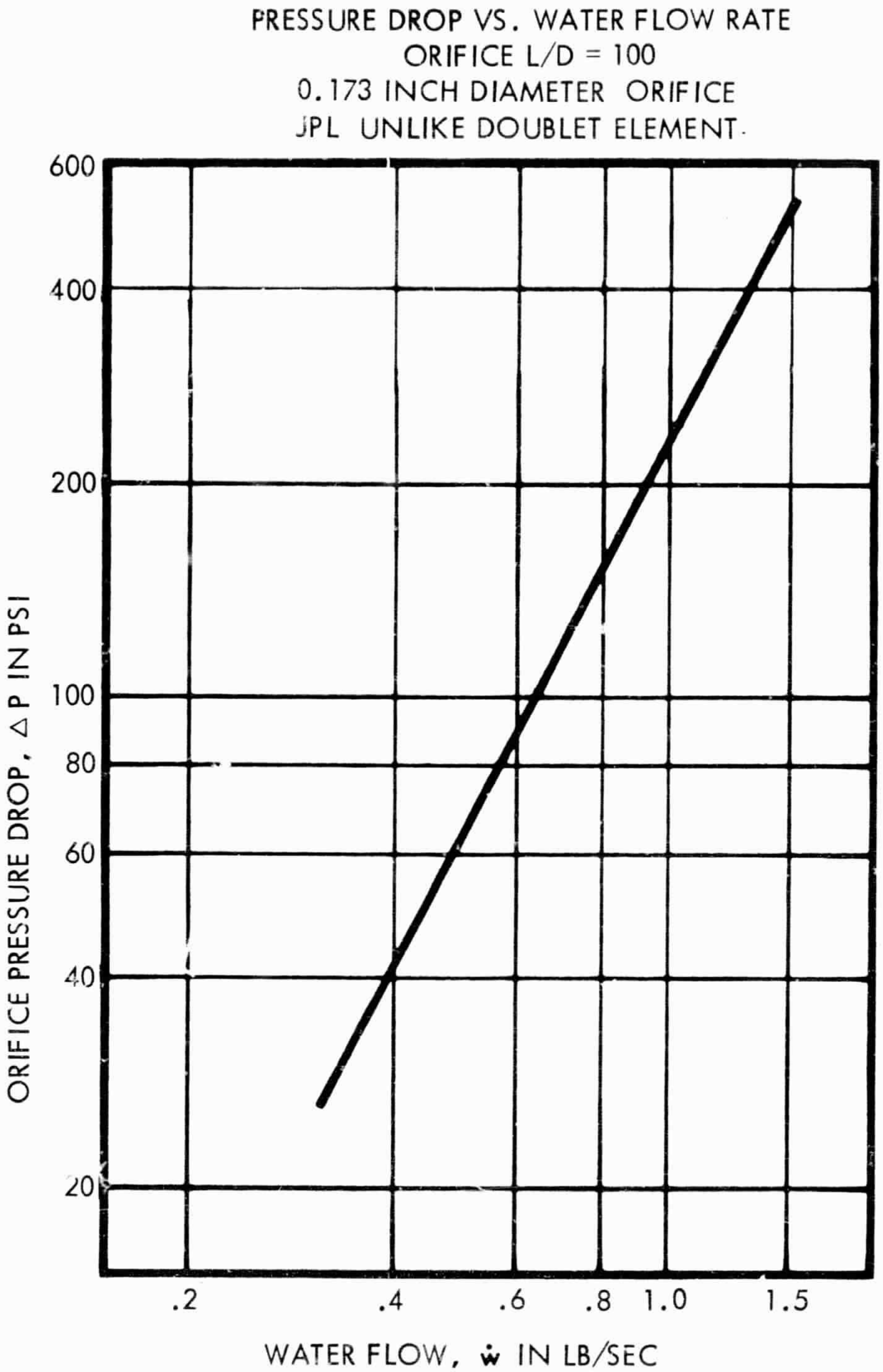

Figure 3-13. Water flow characteristics of the JPL single element injector

4. EXPERIMENTAL RESULTS

4.1 COLD FLOW TESTS

Holographic experimentation at the JPL-ETS was initiated in November 1967. A series of water flow tests were conducted as a convenient means of checking alignment of the laser and holocamera optics, as well as establishing the proper sequence of events in the test procedure to be used in the open flame firings.

A total of 24 water flow tests were conducted in which either a hologram or a laser illuminated photograph recording was attempted. The operating conditions for these preliminary water flow tests are tabulated in Table I. Of the 24 tests made, 17 successful recordings were obtained: a total of 9 holograms and 8 laser illuminated photographs. Table I describes the viewing station (i.e., the region of the impingement point or, a scene volume 12 inches downstream from the impingement point) and indicates the viewing angle (either the fan plane, the fan edge, or an oblique view).

Photographs of the test apparatus with water flowing through the injector element are shown in Figures 4-1 and 4-2. In Figure 4-1, the injector element is installed such that the spray fan is perpendicular to the scene beam of the holocamera. This particular photograph is representative of a relatively low total flow condition (in the order of 1.2 lb-H_2O/sec). Figure 4-1 also clearly shows the installation of the 15-inch diameter focusing lenses suspended from the 6-inch diameter support structure through which the reference beam passes.

Figure 4-2 illustrates the installation of the injector element 90 degrees away from the position shown in Figure 4-1. The spray fan is now oriented in a horizontal plane within the scene beam. Note that a large piece of acrylic sheet has been placed in front of the window leading to the film plate holder. This was done to obtain a qualitative indication of the amount of impingement upon the window from the spray fan when it is oriented in the horizontal plane. During a two-second duration flow test, it was determined taht a relatively small amount of water impinged upon the acrylic. It was concluded from these experiments that open flame

Table I. Water Flow Test Summary

Run No.	Date	Viewing Station	Viewing Angle	P_{TO} psi	P_{TF} psi	Total Flow $\dot{\omega}$ lb/sec	Type of Record	Remarks
B1113A	11-30-67	Impingement Pt.	Fan Plane	125	125	1.37	Hologram	Holograms were not recorded for tests A, B & C. For test C, TRW power supply was disconnected and only ETS power supply used. Shutter open micro-switch to be used to fire laser. Sequence timer fire signal removed by setting "offtime" to zero.
B	"	" "	" "	125	125	1.40	"	
C	"	" "	" "	128	128	1.42	"	
D	12-5-67	" "	" "	83	96	1.19	"	Holograms and photographs were not recorded on tests D, E & F. Laser may be firing too soon. For Test G, a new electrical cable was used from TRW control console to camera to isolate fire signal from shutter solenoid signal.
E	"	" "	" "	94	99	1.25	"	
F	"	" "	" "	85	85	1.17	Photograph	
G	"	" "	" "	90	94	1.21	Hologram	
H	"	" "	" "	107	107	--	"	
I	"	" "	" "	275	320	2.35	"	
J	"	" "	" "	285	330	2.43	"	
K	"	" "	" "	293	338	2.42	Photograph	Lost photograph - Laser out of alignment
L	12-6-67	" "	" "	85	94	1.22	"	
M	"	" "	" "	270	312	2.34	"	
N	"	" "	" "	280	326	2.38	"	
O	"	" "	Fan Edge	96	96	1.23	"	
P	"	" "	" "	80	87	1.17	"	
Q	"	" "	" "	95	95	1.227	Hologram	
R	"	" "	" "	95	95	1.22[illegible]	"	
S	"	" "	Oblique-10°	91	92	1.19	"	
T	"	" "	" "	91	92	1.19	Photograph	
U	"	12" Downstream	Fan Plane	92	93	1.21	"	
V	"	" "	" "	99	100	1.264	Hologram	
W	"	" "	" "	277	323	2.39	"	
X	"	" "	" "	279	322	2.39	Photograph	

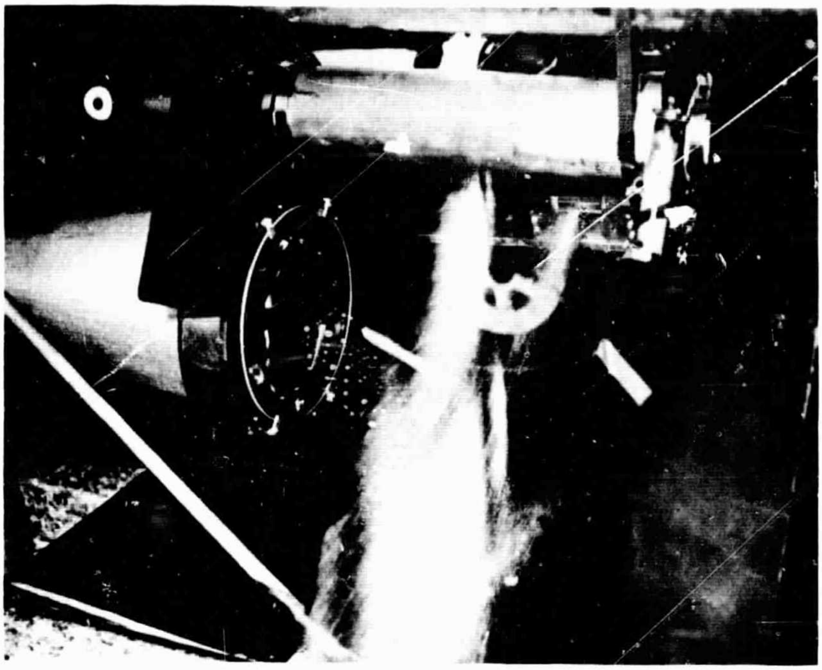

Figure 4-1. Injector water flow test with the spray fan perpendicular to the scene beam of the holocamera

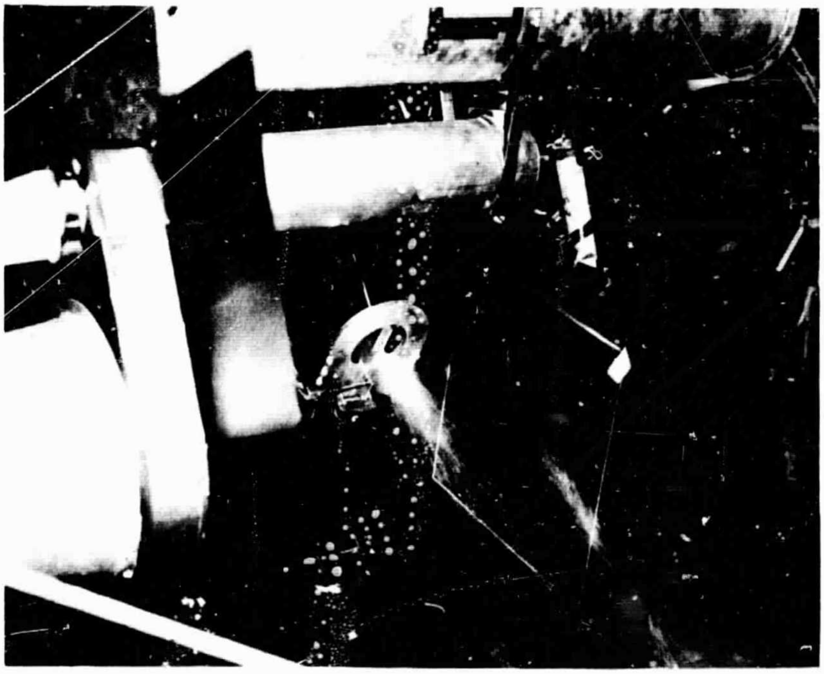

Figure 4-2. Injector water flow test with the spray fan oriented 90 degrees from that shown in Figure 4-1.

test holograms could be made of the edge view of the spray fan without serious risk to the basic apparatus.

Subsequent open flame testing confirmed this conclusion. The same technique was applied, in that acrylic sheets were placed in front of the 15-inch-diameter focusing lenses and the film holder viewing port opposite. It was noted that with the N_2O_4-50/50 N_2H_4-UDMH propellant combination, there was an almost imperceptible amount of discoloration to the acrylic sheets after several firings. When the FNA-UDMH propellants were fired, however, the deterioration of the protective acrylic sheets became more evident. The acid tended to chemically attack the acrylic, and the sheets had to be replaced periodically. Splatter on the windows appreciably degraded the visibility of the reconstructed scene.

Photographs and holograms were recorded on fine grain Eastman 649F and Agfa 10E75 film plate. The Agfa 10E75 plate is about 20 times faster film than the Eastman 649F. Both types of film plates were processed in HRP developer diluted 1:4 in water. Developing times for holograms using the Eastman film averaged between 5 and 8 minutes depending upon the exposure. Holograms with the Agfa plate, on the other hand, required only 30 to 40 seconds developing time. Some experimentation was conducted using dilutions of the HRP developer to as much as 1 part developer to 20 parts of water; however, the development time required for the Agfa film plate holograms was still in the order of 45 seconds. In order to cut down on the exposure the ruby amplifier was removed and only emission from the oscillator was used to record the film. However, near the end of the test program, the scene beam was attenuated by a filter to effect a more favorable scene/reference beam ratio. Following this modification, development time for the Agfa 10E75 film plate was typically in the order of 4 minutes.

Development times with the Agfa film plates used to make the laser illuminated photographs ranged from 2 minutes to 8 minutes with HRP developer in a 1:4 dilution. Control of the developing process was quite adequate with these developing times.

The photograph in Figure 4-3 was made from the reconstruction of a water flow hologram (Run No. B1113I) recorded on Agfa 10E75 film plate during the first portion of the test program. The reconstructed scene was

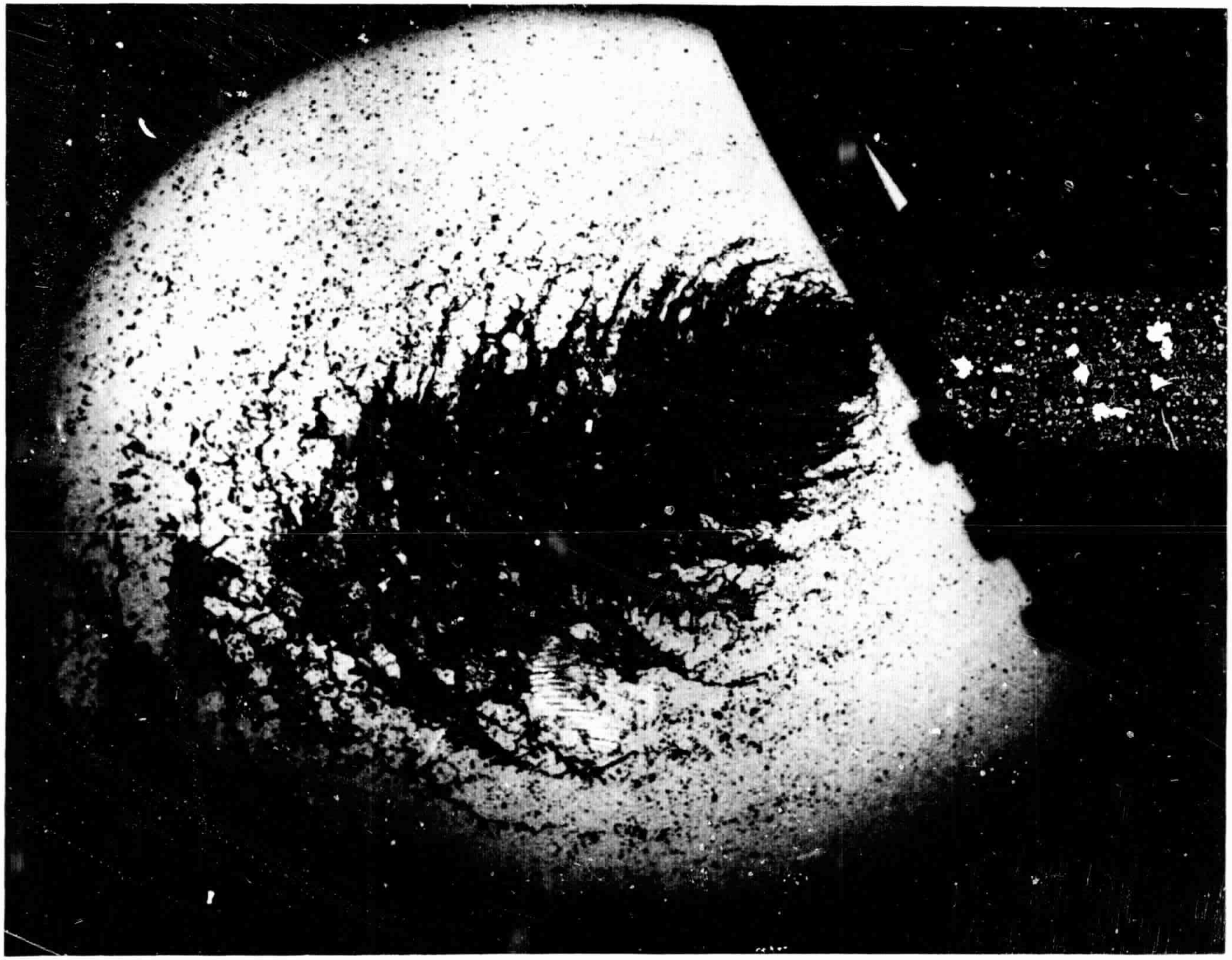

Figure 4-3. Photograph of the reconstruction of hologram B1113I. This photograph illustrates the water flow spray pattern from the single element impinging stream injector operating at a pressure drop of approximately 300 lb/in^2 and a flow rate of 2.35 lb/sec.

photographed on Polaroid Type P/N 55 film with a bellows copy camera, using a Schneider-Kreuznach Componon 300 mm, f/5.6 lens. The copy camera was focused on a plane passing through the impingement point and central portion of the spray fan. This hologram is typical of the various recordings made during the water flow test series.

The photographs shown in Figures 4-4 through 4-6 illustrate the results obtained from making laser illuminated photographs of various water flow tests. To make these photographs, the reference beam of the holocamera was blocked and only the scene beam utilized. As described earlier, a view camera was positioned on a mounting bracket provided adjacent to the film plate holder used for recording holograms. The film plate holder was removed and the installed view camera focused on the impingement point of the injector element. For these photographs the laser illuminator was operated with a ruby amplifier in order to obtain the most emission.

Figure 4-4 is a photograph of the spray fan produced during Run B1113L. The total water flow rate for this run was approximately 1.22 lb/sec. The scene was recorded on Agfa 10E75 film plate and developed in HRP developer for about 5 minutes. The photograph of Figure 4-5 is a similar view of the water spray fan (Run B1113M) except that the total water flow rate for this test was 2.34 lb/sec. The increased mass flow of this test is evident when one compares this photograph with that of Figure 4-4. The same film plate and developer were used as noted for the preceding figure. Development time was increased to approximately 8 minutes, however, resulting in a more dense image on the film plate of Figure 4-5.

The photograph of Figure 4-6 depicts an edge view of the spray fan. In this instance, the injector was oriented 90 degrees from that of the photographs of the two previous figures. This photograph was made during Run B1113P again, using Agfa 10E75 film plate and HRP developer. The total flow rate for this test was about 1.17 lb/sec. Note the scale in the lower left-hand corner of the photograph which was used as a reference device. One can also detect some granularity in the background of the photograph which is characteristic of the coherent light produced by the laser.

Four laser illuminated photographs were made of the water droplet dispersion approximately 12 inches downstream from the injector element. Figure 4-7 illustrates the droplet pattern of such a test (Run No. B1113U).

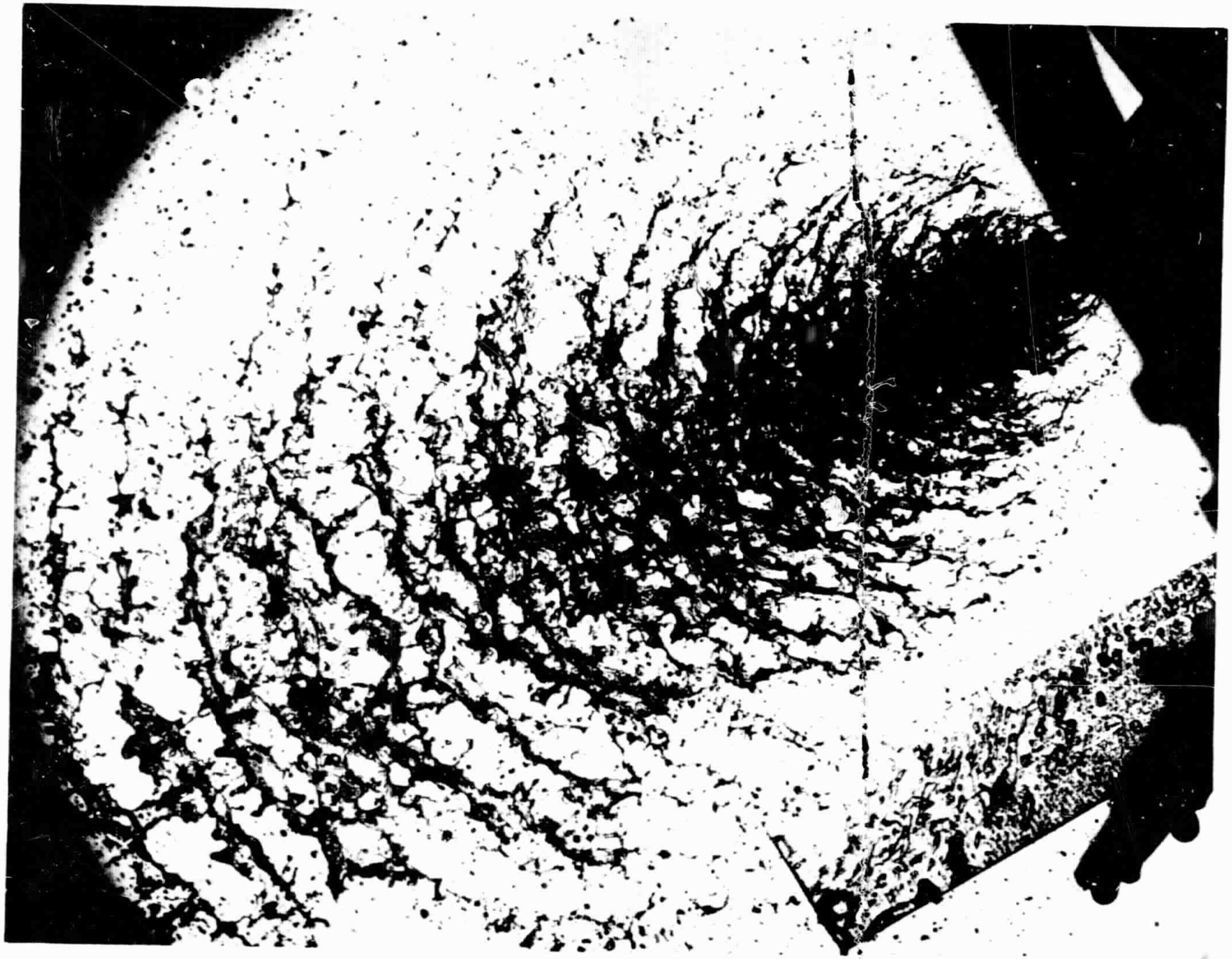

Figure 4-4. Laser illuminated photograph of the water spray fan produced from a single element doublet during Run B1113L

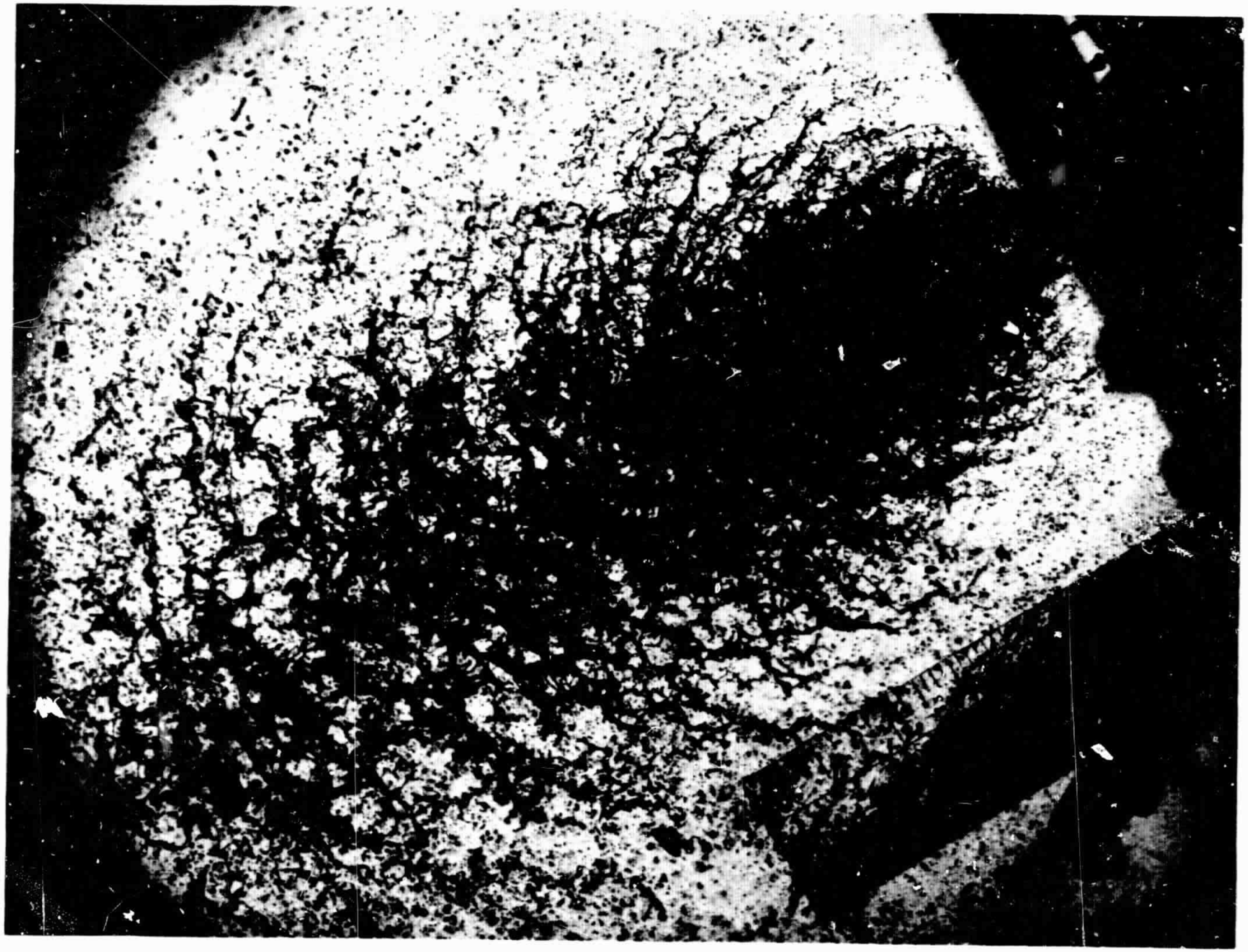

Figure 4-5. Laser illuminated photograph of the water spray fan produced from a single element doublet during Run B1113M

Figure 4-6. Laser illuminated photograph from Run B1113P showing the edge view of the water spray fan produced by a single element doublet

The photograph was made on Agfa 10E75 film plate and developed for 2 minutes in HRP developer diluted 1:8 at 72°F. The photograph used for Figure 4-7 was made by contact printing the Agfa film plate using Kodak Velox printing paper. The film plate was subsequently examined with the aid of a microscope, and a preliminary assessment indicated a resolution of about 25 microns.

4.2 OPEN FLAME TESTS

After the completion of the water flow experiments, the open flame combustion tests were initiated. Testing was conducted with two propellant combinations (N_2O_4 and 50/50 N_2H_4-UDMH, and FNA-UDMH) at ambient sea level conditions. Following these tests, propellant temperature conditioning equipment was moved into the test stand area and both propellant combinations were fired at elevated temperatures. For these latter tests, the propellants were conditioned to temperatures of approximately 80 to 100°F prior to each firing. The holographic results of this part of the Phase I test program are described in succeeding paragraphs.

A total of four open flame tests were conducted in December 1967, at which time an attempt to record a hologram was made. The operating conditions for these and all subsequent open flame tests are tabulated in Tables II and III at the end of Section 4. The film used for these tests was Agfa 10E75 with a Wratten No. 70 gelatin filter placed over the film plate. The first three open flame tests resulted in a heavy "fogging" of the Agfa film plate. On the fourth test (Run B11142[illegible]), a very weak image was obtained on the film plate. Again, the fogging obscurred the recorded image to the extent that it was virtually unusable.

It was presumed that excessive ambient light was reaching the film plate both prior to and after the actual test firing exposure.* A considerable amount of elapsed time occurred (in the order of 15-20 minutes) from the point when the safety slide on the film holder was removed, prior to the test run, and subsequently replaced at the end of each test firing sequence. During the elapsed time in question, the immediate rocket test stand area was cleared of all personnel for reasons of safety.

*"Producing Holograms of Reacting Sprays in Liquid Rocket Engines", Contract No. 952023, Fifth Monthly Progress Report, dated 15 January 1968.

Figure 4-7. Photographic print made from a laser illuminated photograph taken of the water flow from the JPL single element injector during test number B1113U. Direction of droplet flow is from the upper right-hand corner of the photograph to the lower left-hand portion. Examination of the Agfa 10E75 film plate (from which this print was made), under a microscope, indicated a resolution of around 25 microns.

Subsequent test exposures of film plate tended to confirm that ambient light was contributing to the fogged condition of the film. As a result, the large "capping shutter" (described in a previous section of this report) was installed so as to cover the view port on the film-holder housing of the holocamera. The leaf-type capping shutter was solenoid operated and synchronized to open approximately 400 milliseconds prior to triggering the laser. The shutter was programmed to close about 100 milliseconds after the laser pulse.

In addition to the "capping shutter", a new focal plane shutter was installed adjacent to the film holder, which reduced the exposure time of the film plate to the combustion process from about 200 milliseconds to between 50 and 100 milliseconds. Attention was also given to sealing the edge joints of the sheet metal housing in which the film holder was mounted to further reduce ambient light leakage onto the film plate.

A second problem area centered about the maintenance of laser alignment. It was postulated that pressure waves from the open flame combustion acting against the 15-inch-diameter focusing lenses and the film-holder housing might be inducing the laser misalignment experienced after each test firing. To determine whether vibrational loads were imposed on the holocamera during the open flame tests, accelerometers were placed on the equipment including the laser. As a result of this experiment, it was determined that there were no discernable loads on the holocamera due to the combustion process. Indeed, the most significant vibrational forces occurred upon discharge of the flash lamps in the laser.

Coincident with this experiment, the laser rail was mechanically decoupled from the holocamera. This modification completely removed the laser misalignment problem. It and the other improvements previously mentioned, resulted in the production of the first successful hologram of open flame combustion phenomena.

Figure 4-8 is a photograph of the reconstruction of a hologram made during Run No. B1115Q. The hologram was made with Agfa 10E75 film plate and developed for approximately 60 seconds in HRP developer. The hologram was reconstructed with the light from a Spectra Physics helium-neon laser, and photographed with a bellows copy camera using a 300 mm, f/5.6

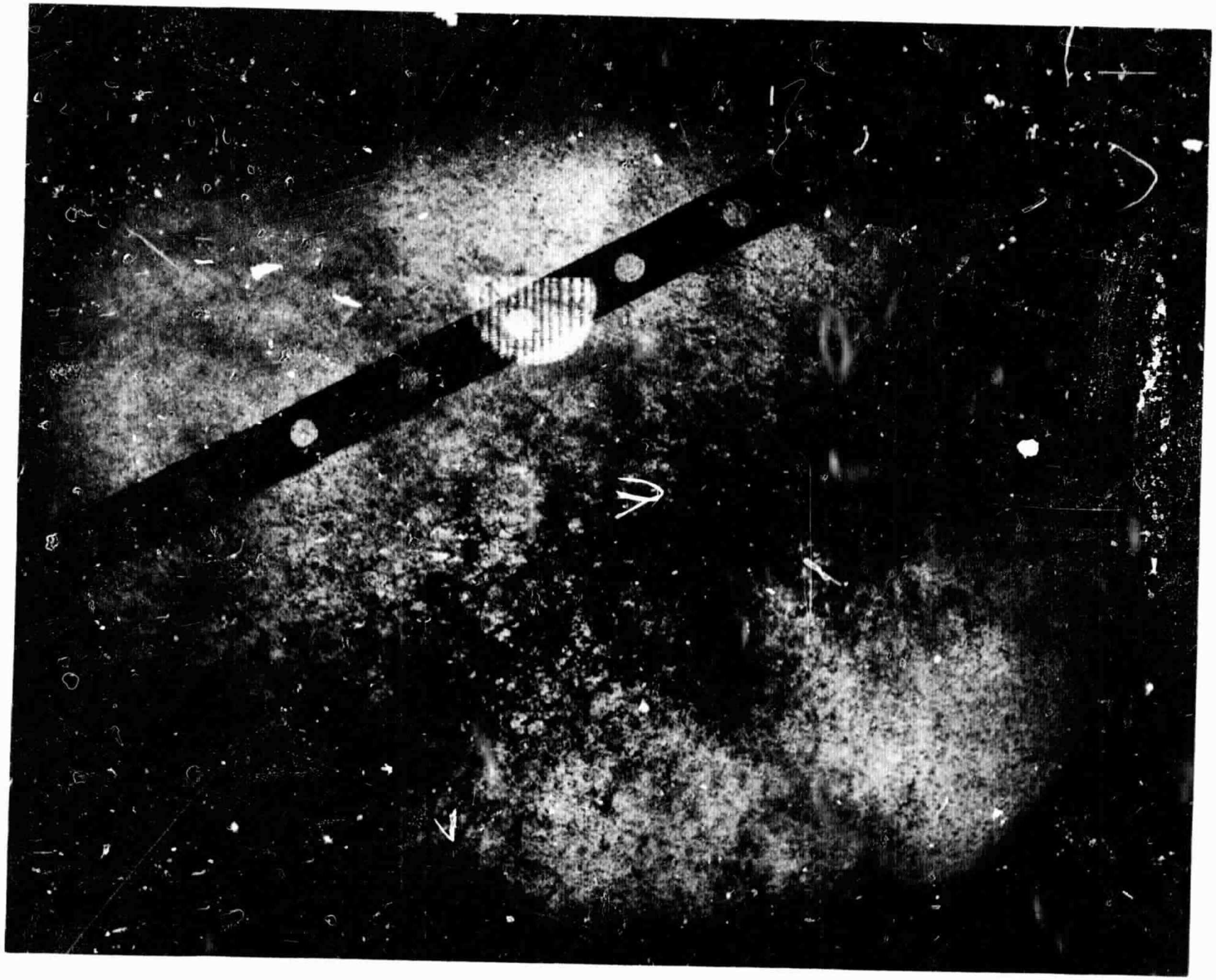

Figure 4-8. Photograph of the reconstruction of a pulsed ruby laser hologram recording of the combustion phenomena during Run B1115Q. The photograph shows the burning droplet dispersion of the fan plane of a single element injector firing N_2O_4 and 50/50 N_2H_4 - UDMH propellants.

Schneider-Kreuznach Componon lens (S/N 5084621). The lens setting for this photograph was f/8 and the film used was Polaroid Type P/N-55

The propellants used in test run B1115Q were N_2O_4 and 50/50 N_2H_4-UDMH. The reconstruction photograph (Figure 4-8) shows the combusting droplet pattern produced by a total flow rate of 2.732 lb/sec at an overall 0.79 mixture ratio (O/F). The general direction of droplet breakup and flow is from right to left in the illustration.

The "viewing station" for this hologram was the impingement point and the region immediately down stream (approximately 8 inches). The viewing angle is that of the major axis of the resultant spray fan.

In making the reconstruction photograph, the copy camera was focused on the dark strip running diagonally across the picture. This strip is a 1/2-inch-wide steel bar with 1/2-inch-diameter holes drilled on 1-inch centers. It was placed in the original test scene to permit the viewer to estimate the magnification of subsequent reconstruction photographs.

Again returning to Figure 4-8 the reader will note a light (pattern-like) spot or imperfection located on the steel bar in the photograph. This is an imperfection in the hologram caused by reflection of the reference beam from the hologram and then from the protective acrylic sheet or window on the holocamera housing. In viewing the reconstructed hologram, this glare or imperfection is seen as a small point of light whose source appears to be at infinity.

When photographically copying the reconstruction, a two-dimensional focal plane is selected for reproduction on the film. What is seen in the resulting photograph then, is the reconstruction of the glare (light reflection) wave interference patterns at a given focal plane within the scene volume. This type of hologram imperfection ("beauty mark") is seen on other reconstructions photographs appearing in this report. Toward the end of the Phase I test program, the glare was eliminated from the hologram by replacing the plexiglass window by a glass one and installing a Polaroid filter. Examples of these reconstructed holograms are also presented.

Figure 4-9 is a photographic reproduction of the high speed recording oscillograph trace from Run 2 B1115Q. As may be seen from the small inset photograph on the trace, this is the same hologram reconstruction (Figure 4-8) discussed in the preceding paragraphs. This oscillograph trace is representative of the various open flame tests and shows graphically the sequence of events which took place.

The oscillograph trace shows that 300 milliseconds following the first indication of the propellant valve opening, the holocamera capping shutter was opened. Approximately 400 milliseconds later, the focal plane shutter was actuated which, in turn, triggered the laser (via a micro-switch). The laser pulse occurred some 30 milliseconds after the focal plane "shutter open" signal was completed. The focal plane shutter signal trace indicated that approximately 90 milliseconds were required to fully open the shutter.

The reconstruction photographs presented in Figures 4-10 and 4-11 were made from holographic recordings of the edge-view of the combusting spray fan. In other words, the view of the resultant spray fan in these two photographs is 90 degrees from that seen in Figure 4-8 discussed in the preceding text. Again, both illustrations (Figure 4-10 and 4-11) represent holograms recorded on Agfa 10E75, developed in HRP developer and subsequently reconstructed with a helium-neon gas laser. The method of photographing the reconstruction is the same as that described for Figure 4-8.

The photographs of Figures 4-10 and 4-11 are interesting to compare because of the strikingly different events taking place. Figure 4-10 illustrates what appears to be a rather orderly combustion process, in that approximately 2 inches downstream of the impingement zone, droplet formations are readily discernible and somewhat uniformly distributed. In marked contrast with this photograph is the photograph shown in Figure 4-11. Examination of this photograph reveals a significant disruption of the mass of burning propellants into two separate and distinct regions. Note also the wave patterns formed in the lower divergent mass flow. For convenience, the operating parameters associated with these two test runs have been extracted from the complete listing for all firings, which may be found in Table II.

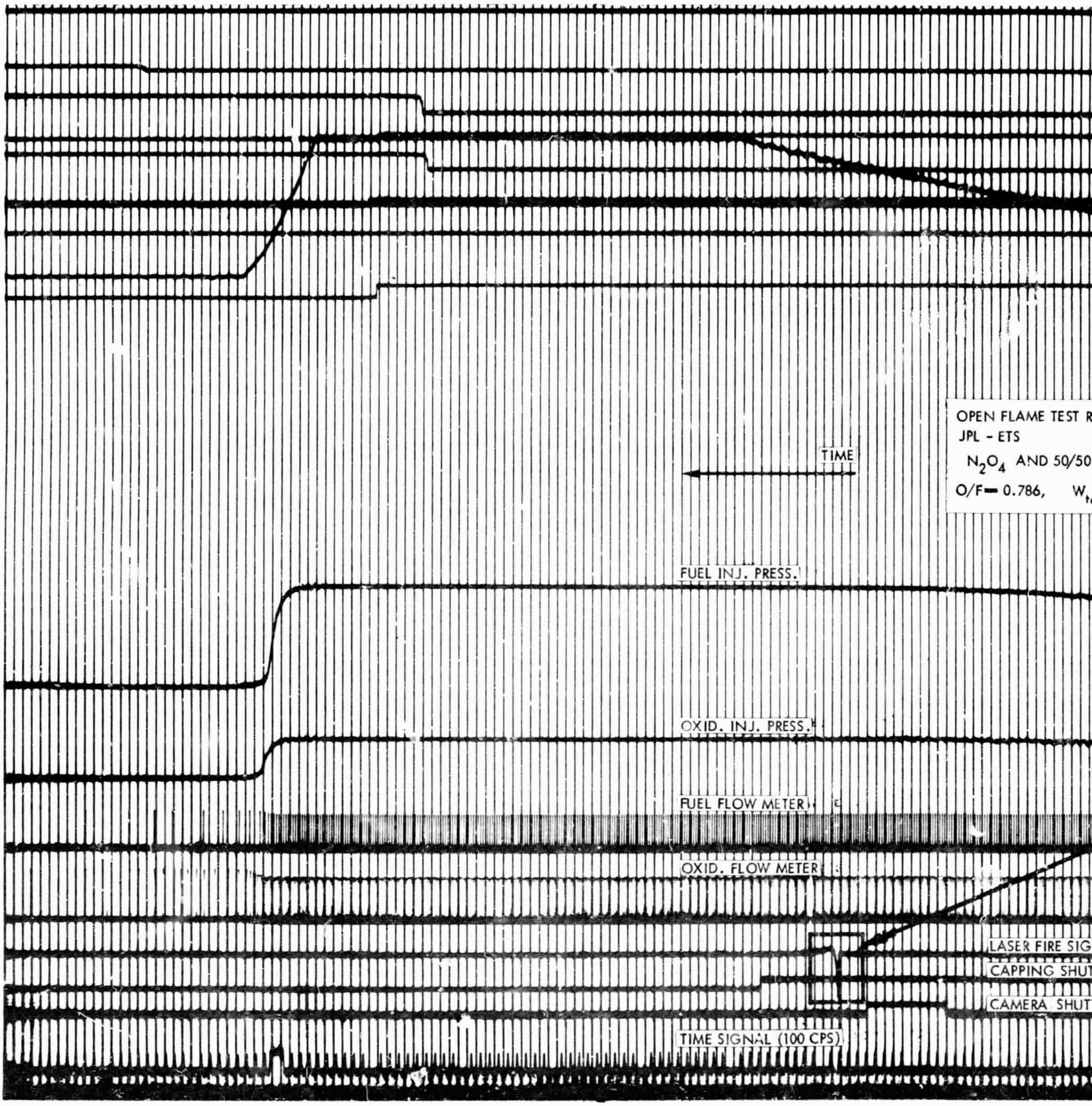

Fig. 4-9. A

FOLDOUT FRAME

42 - A

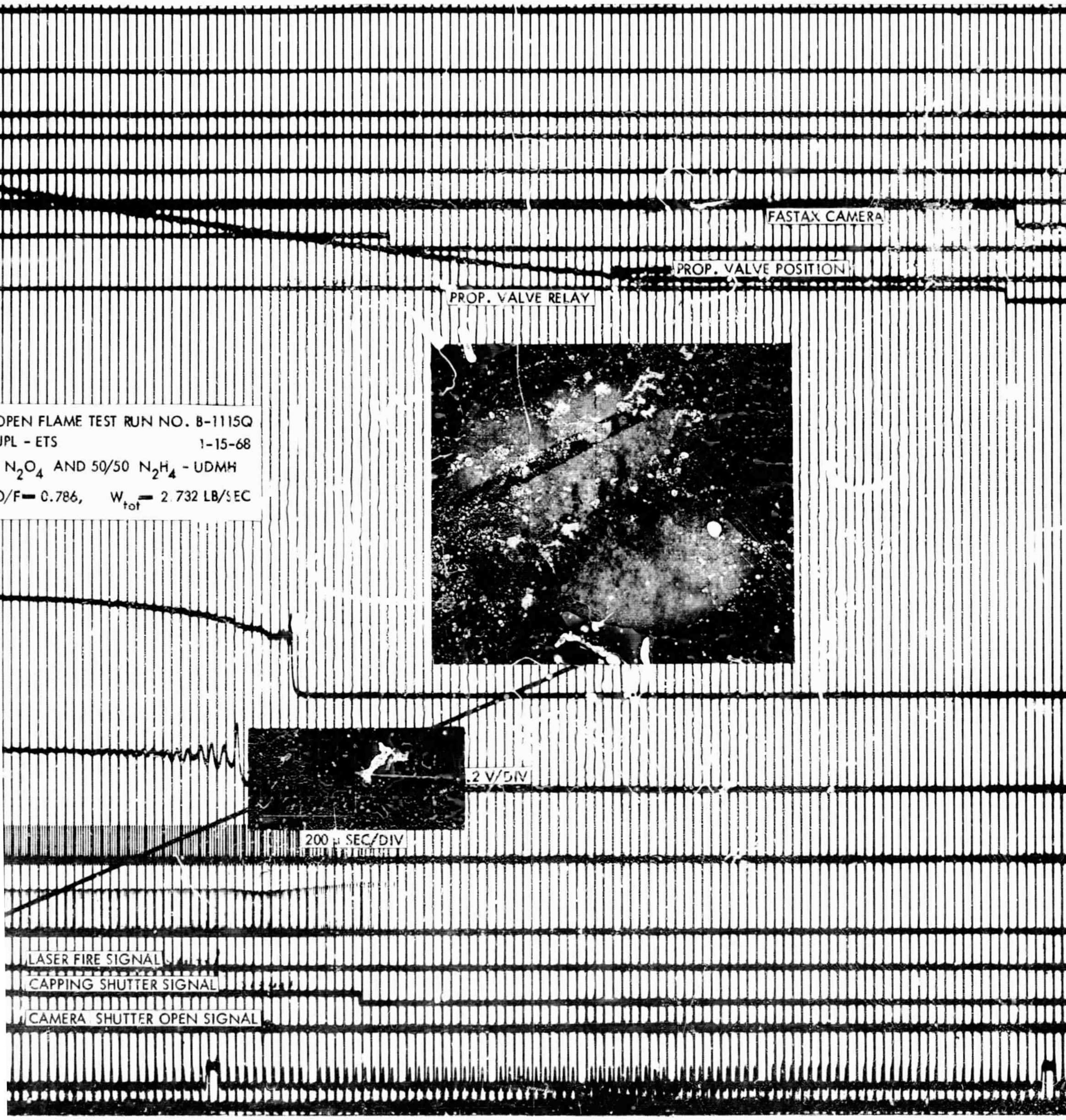

Figure 4-9.B Photographic reproduction of the high speed recording oscillograph from open flame test Run No. B1115Q

FOLDOUT FRAME

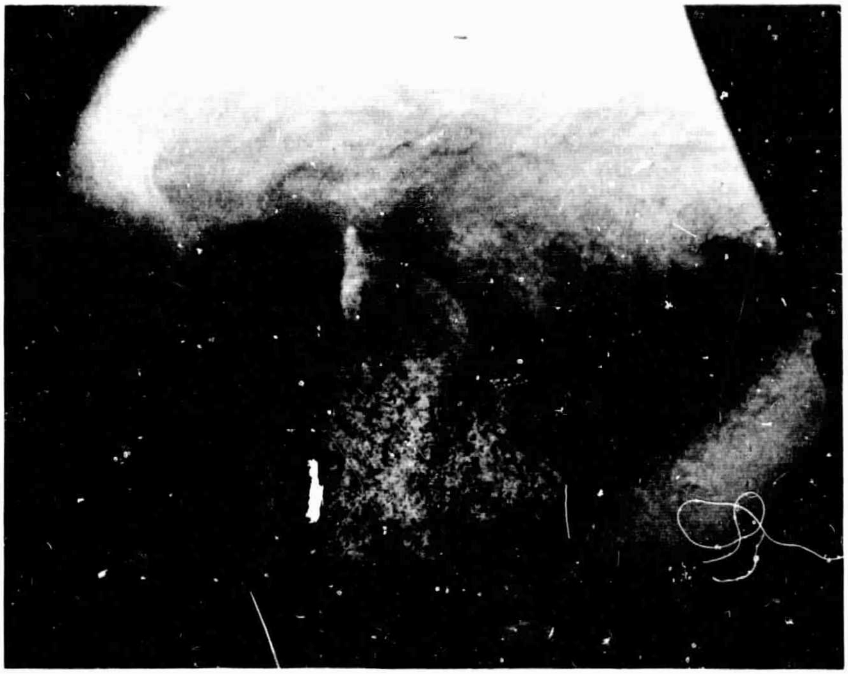

Figure 4-10. Reconstruction photograph of the edge-view of the combustion spray fan recorded on N_2O_4-50/50 N_2H_4-UDMH firing No. B1115I

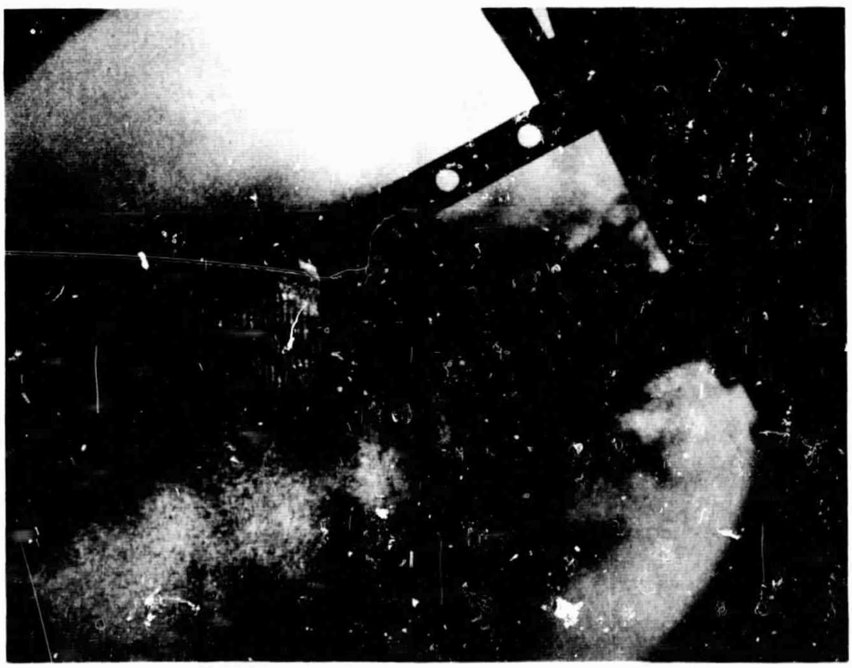

Figure 4-11. Reconstruction photograph of the edge-view of the combustion spray fan recorded on N_2O_4-50/50 N_2H_4-UDMH firing No. B1115R

Parameter	Run No. B1115I	Run No. B1115R
Oxidizer	N_2O_4	N_2O_4
Fuel (50/50 Blend)	N_2H_4 - UDMH	N_2H_4 - UDMH
Mixture Ratio, O/F	1.359	1.219
Oxidizer Flow Rate, lb/sec	0.893	1.576
Fuel Flow Rate, lb/sec	0.657	1.292
Injector Velocity, Ave. ft/sec	65.4	122.5
Oxidizer Temperature, °F	57	49
Fuel Temperature, °F	55	56

The photograph of Figure 4-12 was made from the reconstruction of the hologram recorded during test firing No. B1115W. Seen here is the combustion fan plane of FNA-UDMH, burning at an overall mixture ratio of 1.38. The average injection velocity of the free stream propellants was approximately 122 ft/sec. Total propellant mass flow rate for this test was 2.77 lb/sec. The propellants were at ambient temperature (about 53°F) prior to the run.

The combustion process appears orderly and reasonably uniform in this photograph. In the initial stages of reaction (approximately the first 2 inches) the laser illumination does not penetrate the events taking place. It is reasoned that this may be due to: 1) the fact that droplet and ligament density in this region is extremely intense, thus rendering the scene opaque, or 2) the small droplet velocities near the impingement zone are very high and therefore appear as a smear on the hologram film plate. In reality, both effects may contribute to the opaque qualities seen in the photograph of Figure 4-12.

Further review of the photograph shows that quite large droplet wave formations exist for a distance of approximately 2 inches downstream of the opaque core previously described. Seven inches downstream of the impingement zone are large quantities of droplets still in existence. And finally, the reflection described for the photograph of Figure 4-8 is also apparent in this reconstruction. The phenomena is the same as that explained in the earlier figure.

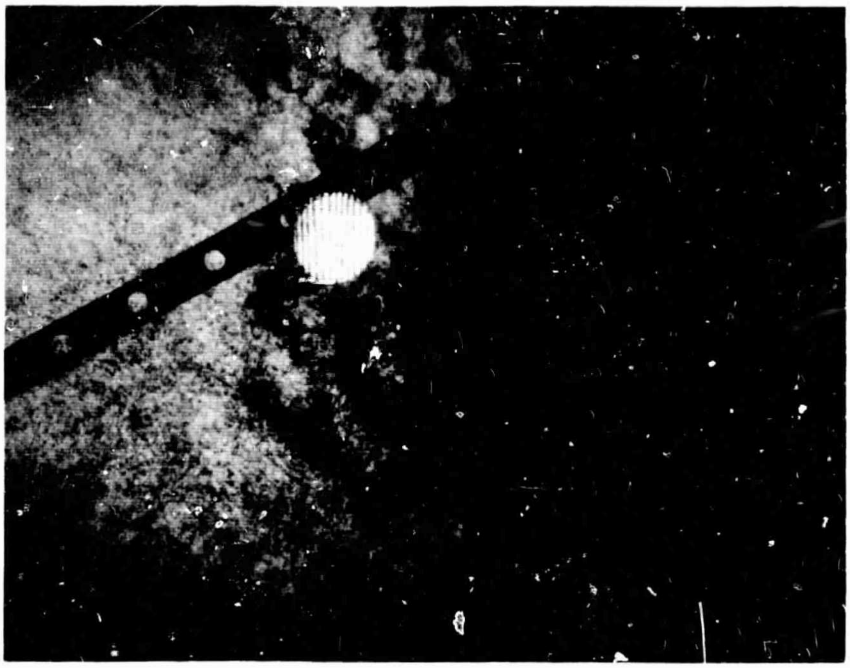

Figure 4-12. Reconstruction photograph of the fan plane view of FNA-UDMH combustion phenomena recording during Run No. B1115W

Several holograms were recorded of the scene volume 12 inches downstream of the injector element, but it was difficult to assess the results of these tests. For the most part, very few droplets could be detected in the reconstructed holograms. Without a systematic investigation of the events taking place at distances of 12 inches or more downstream of the injector, it is impossible to comment on the overall quality of the holograms.

Prior to running the elevated propellant temperature open flame tests, it was decided to make recordings of individual oxidizer and fuel streams emitting from the injector orifices. Typical reconstruction photographs of such recordings are presented in Figures 4-13 and 4-14. Figure 4-13 is a reconstruction photograph of an ambient temperature (46°F) 50/50 N_2H_4-UDMH fuel stream, flowing into the atmosphere. The free stream injection velocity of the fuel jet was 107 ft/sec. About 8 inches of free stream flow appear in the hologram.

The photograph is Figure 4-14 shows a stream of N_2O_4 emitting from one of the injector orifices. This reconstruction photograph was made of a holographic recording of the oxidizer flowing at an elevated temperature (90°F). Both reconstruction photographs (Figures 4-13 and 4-14) were made with the copy camera lens set at f/8 using Polaroid Type P/N 55 film. At this aperture, the granularity effect of the coherent laser light is noticeable.

Figures 4-15 through 4-17 illustrate reconstruction photographs of typical elevated propellant temperature open flame tests. Note that the imperfection or defect (glare) recorded in previous combustion illustrations is not present in these photographs. The defect, caused by a light glare from the acrylic sheets on windows on the holocamera, was overcome by replacing the acrylic with pyrex glass. The combustion heat had caused distortion in the acrylic resulting in the glare recorded on the holograms. The substitution of glass windows eliminated this problem.

Figure 4-15 represents the combustion phenomena recorded during Run No. 51117D. This is an edge-view of the resultant spray fan produced by N_2O_4 and 50/50 N_2H_4 - UDMH pre-conditioned to 92°F. Combustion of the same propellant combination is shown in Figure 4-16. In this instance

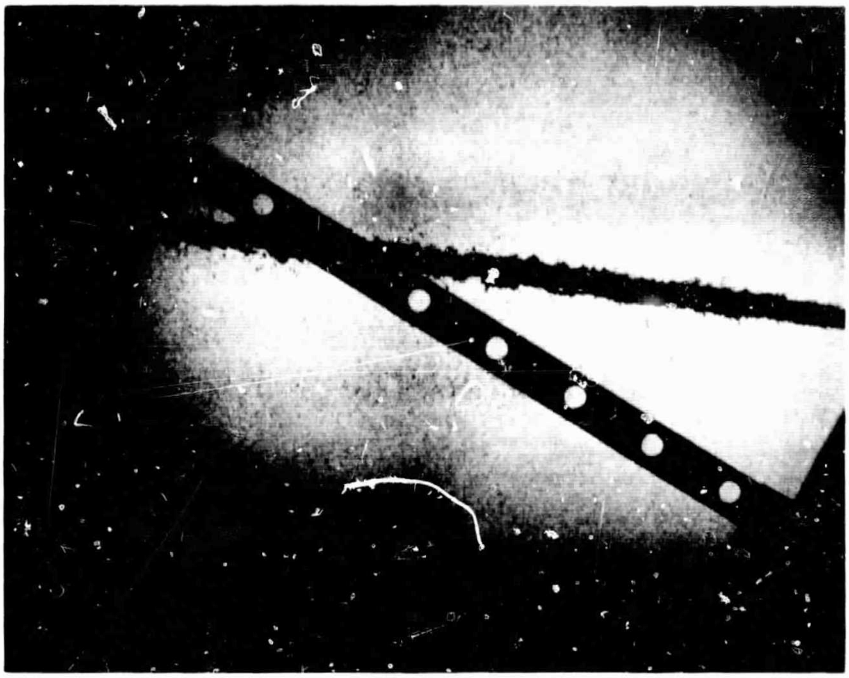

Figure 4-13. Reconstruction photograph of ambient temperature (46^oF) fuel stream flowing into atmosphere

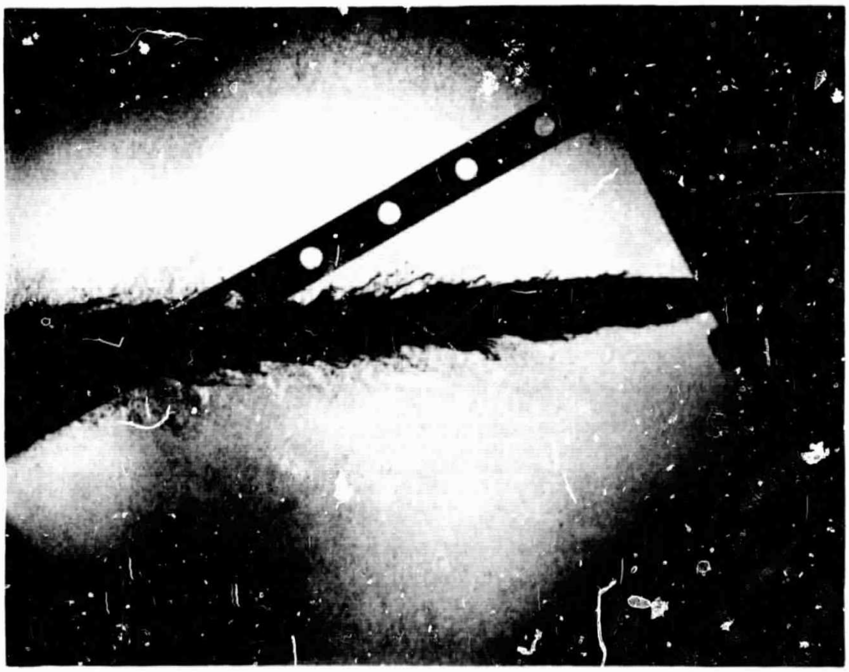

Figure 4-14. Reconstruction photograph of N_2O_4 at elevated temperature (90^oF) flowing into atmosphere

Figure 4-15. Reconstruction photograph of Run No. B1117D showing edge view of N_2O_4-50/50 N_2H_4-UDMH fan during elevated propellant temperature open flame test

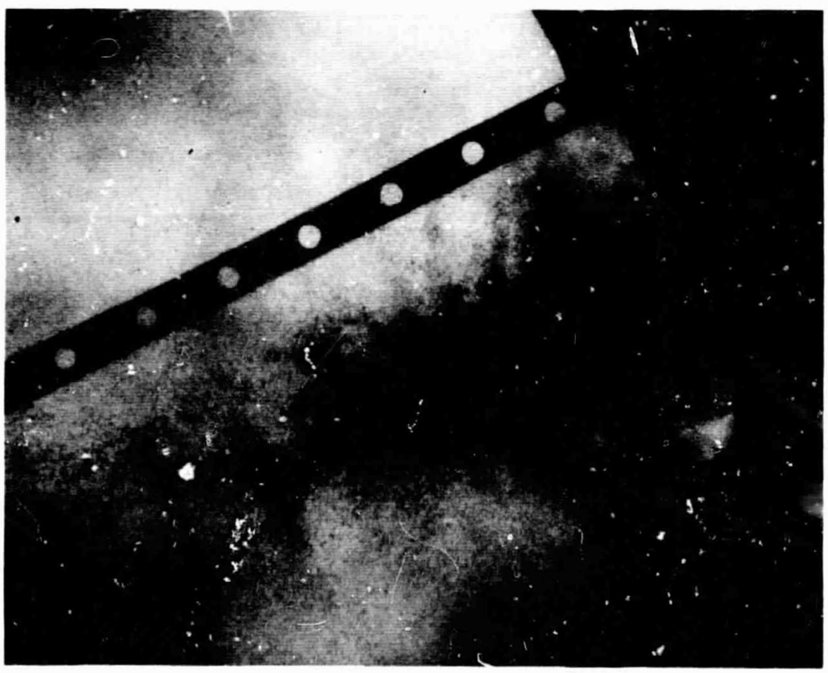

Figure 4-16. Reconstruction photograph of Run No. B1117H showing fan plane of N_2O_4-50/50 N_2H_4-UDMH open flame test during elevated propellant temperature test series

(Run No. B1117H) the view is the fan plane and the propellants were conditioned to approximately 95°F. Note the definite droplet wave formations present in the first few inches of this reaction.

Two photographs of the hologram made during Run No. B11170 are shown in Figures 4-17 and 4-18. The photographs differ in the location (and hence image magnification of the subject matter) and viewing angle of the copy camera. In Figure 4-17, this copy camera was positioned such that the hologram was parallel with, and approximately centered, on the camera format. By contrast, this photograph of Figure 4-18 was made by elevating the copy camera with respect to the hologram and then "looking down" into the hologram scene towards the impingement point of the injector. By so arranging the copy camera, a different perspective of the same event was obtained.

Figures 4-17 and 4-18 illustrate a fan edge-view of the combustion process of FNA and UDMH (Run No. B11170). For this run, the propellants were conditioned to approximately 100°F before the test firing.

Throughout the foregoing text, the feasibility of applying holographic techniques to the recording of open flame combustion has been demonstrated by means of various two-dimensional reconstruction photographs. These photographs clearly show that the laser illuminator provided sufficient light energy to overcome the background radiation of the flame, and allow the events taking place to be recorded on a photographic plate via transmitted light.

One of the most valuable features of holography, however, is the fact that it may be used to record these events in a scene volume. Within this scene volume there are no depth-of-field limitations as with conventional photography. Examination of the events in the three-dimensional scene through the use of conventional photography requires the prior selection of a point or plane of interest within the scene. If additional planes of interest are to be recorded, the test scene must be duplicated in so far as is possible.

Precise duplication of liquid rocket combustion by means of repeated testing is virtually impossible since the phenomenon is largely random in nature. With holographic techniques, however, it is possible to exa-

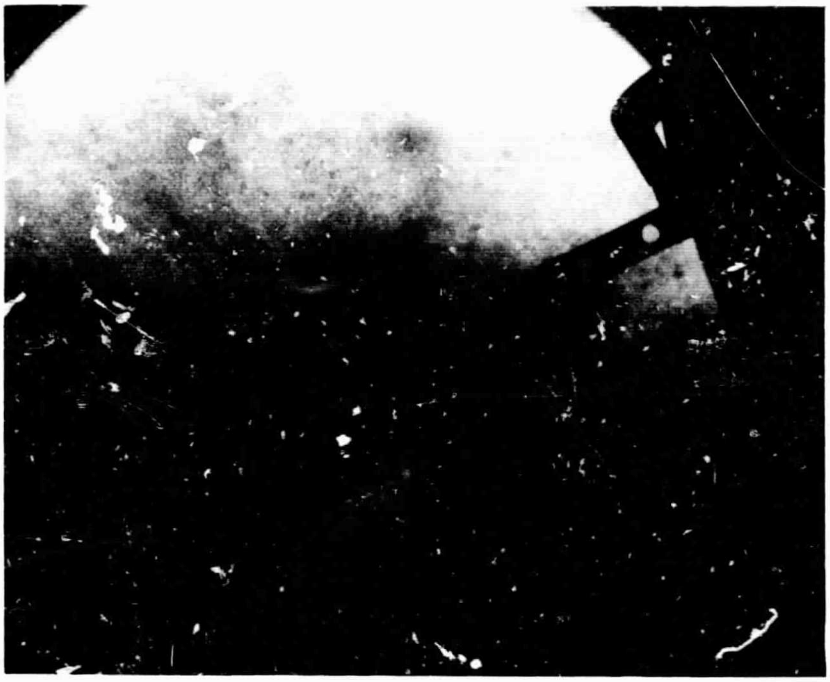

Figure 4-17. Reconstruction photograph of FNA-UDMH fan edge view of hologram made during open flame firing B11170 with propellants conditioned to 100°F prior to testing

Figure 4-18. Reconstruction photograph of Run B11170 taken with copy camera positioned to "look down into the hologram" toward the impingement point

mine (at one's leisure) all of the events simultaneously taking place within the scene volume at the instant the recording was made. This examination process may be done with any conventional optical instrument or simply with the human eye.

Figure 4-19 is an illustration of the three-dimensional characteristics of a hologram. Three reconstruction photographs of the same hologram were made by selecting different focal planes within the scene. Referring to the Figure, it may be seen that the photograph in the center was made by focusing the copy camera on the central portion of the reacting spray. In this instance, the viewer is looking at an edge view of the spray fan recorded during Run No. B1115I. A reconstruction photograph of this firing was discussed previously (see Figure 4-10).

The photograph on the right in Figure 4-19 was made by focusing a copy camera on droplets located in a plane adjacent to the acrylic window protecting the film plate housing on the right side of the holocamera scene volume. The central opaque portion of the initial part of the reacting spray fan appears as a blur located behind these droplets. Conversely, the photograph on the left (Figure 4-19) was made by focusing the copy camera on the droplets at the extreme opposite side of the scene volume. In this photograph, the opaque part of the spray fan is again blurred and out of focus since it is now in the foreground of the scene. Also in sharp focus in this photograph is the grid which was inscribed on the acrylic window protecting the 15-inch-diameter field lenses suspended from the reference beam housing.

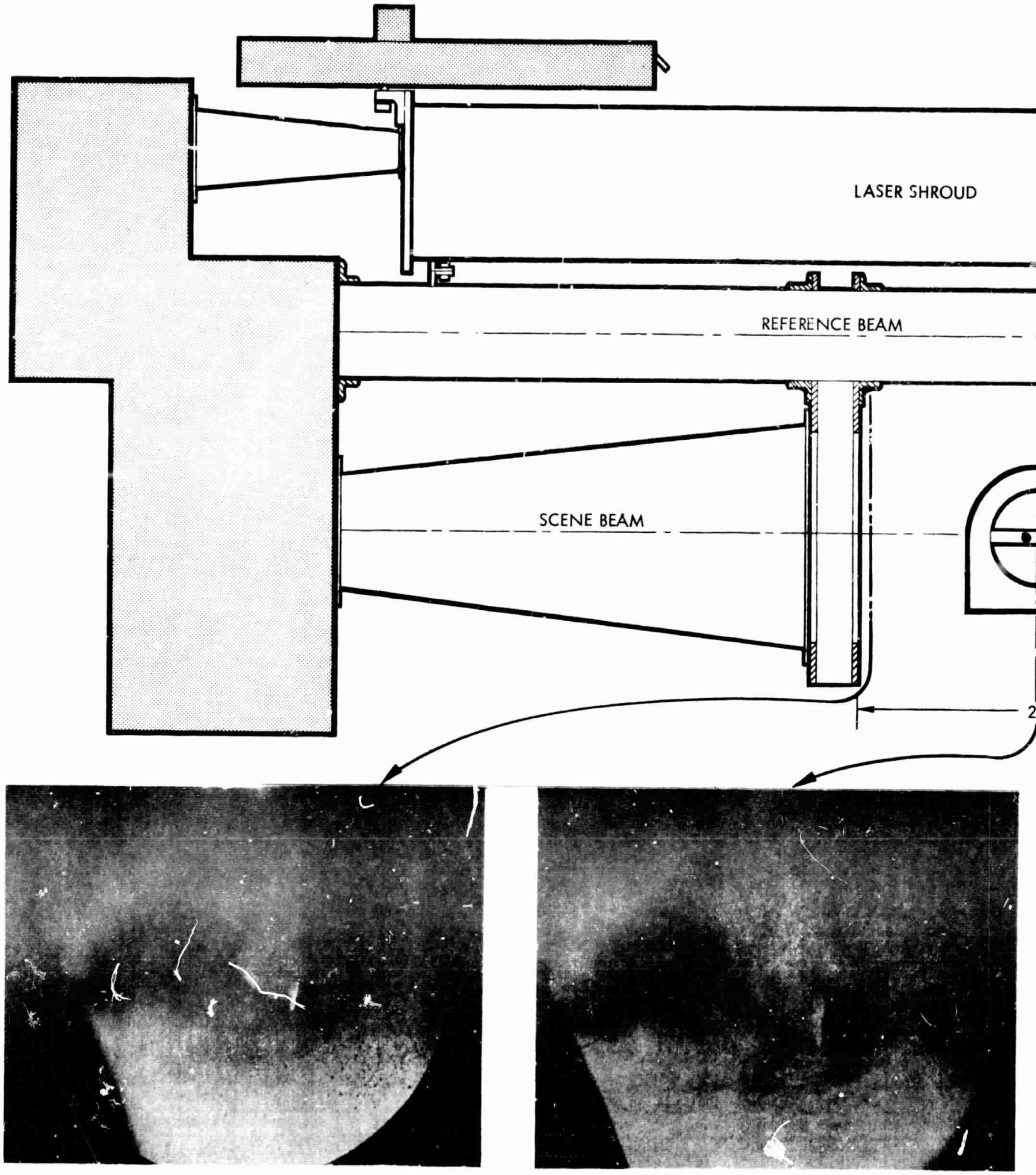

Fig 4-19.A

52-A

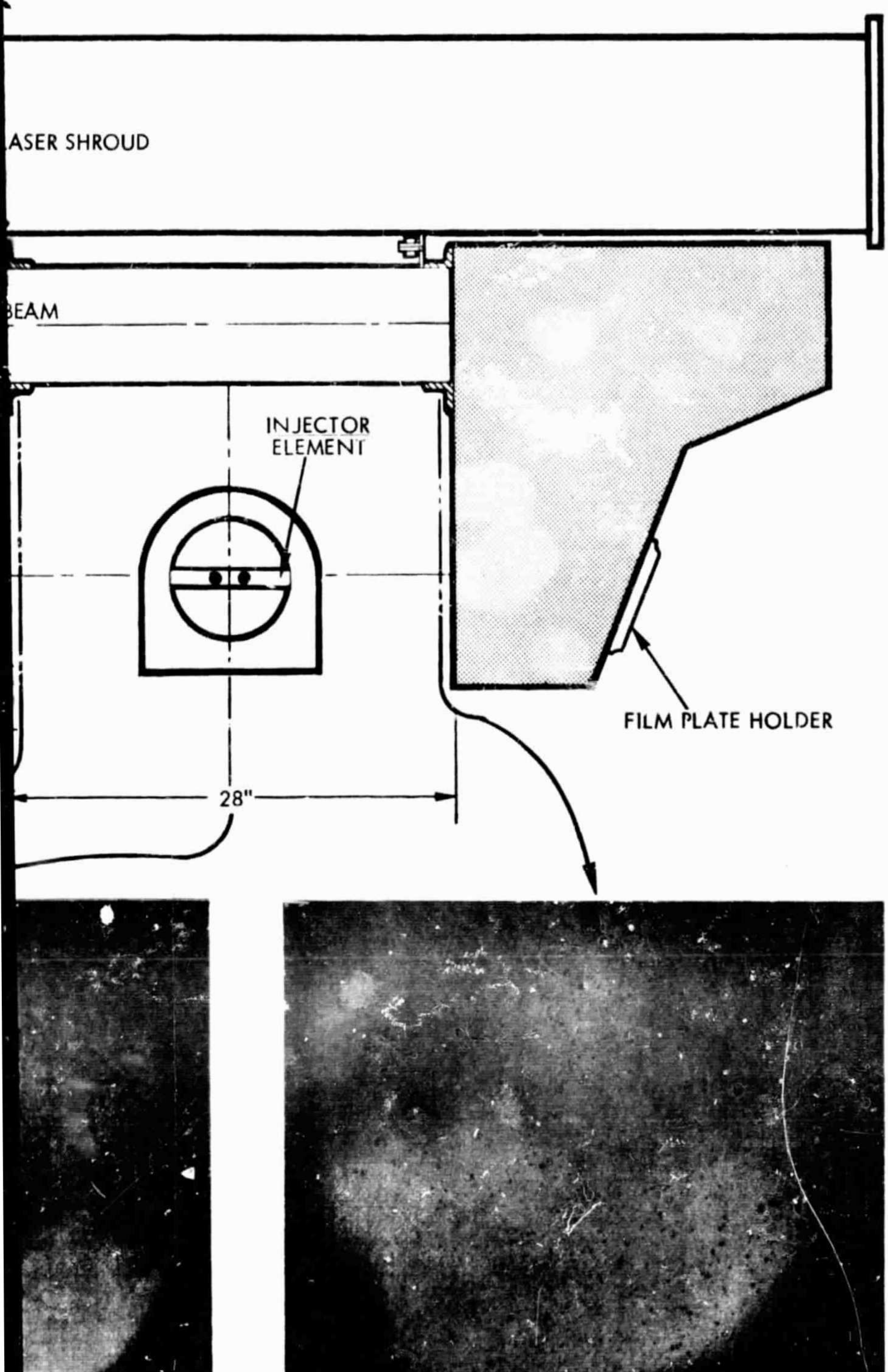

Figure 4-19.B Reconstruction photographs made from open flame test B1115I illustrating three-dimensional characteristics of a hologram

FOLDOUT FRAME

Run No.	Date	Viewing Station	Viewing Angle	P_{TO} Psi	P_{TF} Psi	$\dot{W}_o$ Lb/Sec	$\dot{W}_f$ Lb/Sec	O/F Ratio
B1114F	12-21-67	Impingement Pt.	Fan Plane	145	132	0.863	0.60	1.44
G	"	" "	" "	145	132	0.796	0.623	1.28
H	12-22-67	" "	" "	145	132	0.80	0.61	1.31
I	"	" "	" "	135	132	0.786	0.618	1.24
B1115A	1-8-68	Impingement Pt.	Fan Plane	137	134	0.945	0.619	1.520
B	"	" "	" "	1[illegible]5	135	0.938	0.629	1.491
C	"	" "	" "	136	133	0.943	0.626	1.506
D	1-10-68	" "	" "	131	133	0.916	0.625	1.465
E	"	" "	" "	135	130	0.939	0.618	1.357
F	"	" "	" "	108	175	0.780	0.764	1.021
G	1-11-68	" "	" "	138	130	0.874	0.659	1.320
H	"	" "	" "	109	174	0.793	0.763	1.039
I	"	" "	Fan Edge	139	132	0.893	0.657	1.359
J	1-12-68	" "	" "	166	76	0.967	0.496	1.949
K	"	" "	15° Oblique	106	114	0.778	0.609	1.27
L	"	Downstream	Fan Plane	107	114	0.770	0.606	1.270
M	1-15-68	"	" "	428	460	1.688	1.281	1.31
N	"	Impingement Pt.	" "	377	434	1.574	1.269	1.240
O	"	" "	" "	373	433	1.576	1.269	1.24
P	"	" "	" "	372	428	1.572	1.258	1.249

FOLDOUT FRAME

53-A

TABLE II. A

Table II.B Phase I Open Flame Test Summary: N_2O_4-50/50 N_2H_4 UDMH propellant combination

$\dot{W}_f$ b/Sec	O/F Ratio	V_{ave} Ft/Sec	Prop. Temp., °F Ox/Fuel	Type of Record	Remarks
0.60	1.44		35/40	Hologram	Film plate was fogged
0.623	1.28		35/40	"	" " " "
0.61	1.31		35/40	"	" " " "
0.618	1.24		35/40	"	Very weak image - plate fogged
0.619	1.526	64.7	46/45	Hologram	No hologram obtained
0.629	1.491	65.1	46/46	"	" " "
0.626	1.506	65.1	47/47	"	" " "
0.625	1.465	64.5	53/53	"	Poor holocamera position
0.618	1.357	65.7	52/53	"	Hologram unsatisfactory
0.764	1.021	67.3	52/52	"	Recording of fuel jet only
0.659	1.326	65.1	57/58	"	Good hologram
0.763	1.039	67.8	57/50	"	" "
0.657	1.359	65.4	57/49	"	" "
0.496	1.949	59.3	54/54	"	Adjusted capping shutter, hologram very hazy
0.609	1.277	59.1	54/56	"	Hologram very hazy
0.606	1.270	58.6	54/54	"	Good hologram - few droplets visible
1.281	1.317	125.6	52/50	"	" " - more droplets visible
1.269	1.240	121.4	54/54	"	Double laser pulse - hologram dark
1.269	1.241	121.4	55/55	Photograph	No photograph obtained
1.258	1.249	-	55/58	Hologram	Weak hologram

FOLDOUT FRAME

Run No.	Date	Viewing Station	Viewing Angle	P_{TO} Psi	P_{TF} Psi	$\dot{W}_o$ Lb/Sec	$\dot{W}_f$ Lb/Sec	O/ Rat
B1115Q	1-15-68	Impingement Pt.	Fan Plane	220	593	1.203	1.529	0.7
R	"	" "	Fan Edge	429	375	1.576	1.292	1.2
S	"	" "	" "	572	285	1.948	1.037	1.8
B1117A	1-30-68	" "	Fuel Stream	-	131	-	0.621	-
B	1-31-68	" "	Oxid. Stream	144	-	0.737	-	-
C	2-2-68	" "	Oxid. Stream	147	-	0.712	-	-
D	"	" "	Fan Edge	148	130	0.602	0.633	0.9
E	"	" "	Oxid. Stream	232	-	0.858	-	-
F	2-6-68	" "	Fan Edge	442	450	1.400	1.450	0.9
G	"	" "	Fan Plane	547	451	1.565	1.248	1.2
H	"	" "	" "	151	125	0.699	0.635	1.0
I	"	" "	" "	151	123	0.738	0.625	1.1

54-A

TABLE II. A

FOLDOUT FRAME

Table II.B Phase I Open Flame Test Summary: N_2O_4-50/50 N_2H_4 UDMH propellant combination (Cont'd)

$\dot{W}_f$ Lb/Sec	O/F Ratio	V_{ave} Ft/Sec	Prop. Temp., °F Ox/Fuel	Type of Record	Remarks
1.529	0.786	120.8	56/58	Hologram	Very good hologram
1.292	1.219	122.5	55/56	"	" " "
1.037	1.878	121.5	54/55	"	Hologram weak and hazy
0.62[illegible]	-	-	--/46	Hologram	Single orifice flow only
-	-	-	46/--	"	Single orifice flow only
-	-	-	47/--	"	Single orifice flow only
0.633	0.951	56.2	92/92	"	Good hologram
-	-	-	96/--	"	Single orifice flow only
1.450	0.965	137.6	87/91	"	
1.248	1.254	122.6	95/98	"	
0.635	1.035	58.2	97/96	"	Good hologram
0.625	1.180	59.7	81/91	"	Lost photographic record

FOLDOUT FRAME

Run No.	Date	Viewing Station	Viewing Angle	P_{TO} psi	P_{TF} psi	$\dot{W}_o$ Lb/Sec	$\dot{W}_F$ Lb/Sec	O/F Ratio
B-1115-T	1-16-68	Impingement Pt.	Fan Edge	360	423	1.496	1.225	1.221
U	"	" "	" "	206	571	1.104	1.391	0.793
V	"	" "	Fan Plane	415	390	1.614	1.167	1.383
W	1-17-68	" "	" "	407	382	1.605	1.163	1.380
X	"	" "	" "	641	254	2.035	0.943	2.158
Y	"	" "	" "	102	92	0.784	0.558	1.405
Z	"	" "	" "	161	64	0.987	0.467	2.113
B-1116-A	"	" "	Fan Edge	103	94	0.783	0.563	1.391
B	"	" "	" "	62	127	0.607	0.661	0.918
C	1-18-68	" "	15° Oblique	103	94	0.773	0.558	1.385
D	"	Downstream	Fan Plane	104	94	0.788	0.557	1.414
E	"	"	" "	412	381	1.609	1.161	1.385
F	"	"	" "	414	381	1.619	1.158	1.398
B-1117-J	2-8-68	Impingement Pt.	Oxid. Stream	142	-	0.704	-	-
K	"	" "	" "	167	-	0.839	-	-
L	"	" "	Fan Plane	156	135	0.863	0.611	1.412
M	"	" "	" "	537	449	1.953	1.188	1.650
N	"	" "	Fan Edge	452	445	1.604	1.156	1.387
O	"	" "	" "	159	130	0.811	0.594	1.365

FOLDOUT FRAME

55-A

TABLE III - A

Table III.B Phase I Open Flame Test Summary: FNA - UDMH propellant combination

c	O/F Ratio	V_{ave} Ft/Sec	Prop. Temp. °F Ox/Fuel	Type Of Record	Remarks
5	1.221	122.3	55/54	Hologram	Multiple laser pulse
1	0.793	120.3	[illegible]4/56	"	Hologram poor - acrylic windows etched
7	1.383	122.4	54/56	"	No hologram obtained
3	1.380	121.7	53/52	"	Good hologram - clear but weak
3	2.158	121.8	53/56	"	" " " " "
3	1.405	59.0	55/59	"	" " " " "
7	2.113	59.8	56/60	"	" " " " "
3	1.391	60.8	57/64	"	Good hologram - acrylic windows were di
	0.918	60.0	57/64	"	Good hologram
	1.385	58.4	49/51	"	Poor and hazy - dirty windows
	1.414	59.0	54/54	"	Good hologram - not many droplets vis.
	1.385	121.9	55/56	"	No hologram obtained
	1.398	122.3	56/60	"	Good hologram - droplets not visib
	-	-	90/-	Hologram	Single orifice flow only
	-	-	101/-	"	" " " "
	1.412	66.1	94/95	"	Good hologram
	1.650	137.5	98/100	"	" "
	1.387	124.8	98/100	"	" "
	1.365	63.4	100/95	"	" "

FOLDOUT FRAME

5. CONCLUSIONS

The Phase I experimental program resulted in the design, construction and test of a new and unique pulsed ruby laser holocamera. The feasibility of the holocamera design concept was tested and found satisfactory. More specifically, the feasibility of:

- Producing transmission holograms of burning propellant droplets in the presence of strong background radiation from the open flame combustion was conclusively demonstrated.

- Making holograms of a test scene volume 14 inches in diameter by 26 inches wide (scene volume depth) was demonstrated.

- Recording holograms in broad daylight was shown.

- Producing laser illuminated photographs with the test apparatus was demonstrated.

The resolution capability of the present holocamera system remains to be systematically tested and evaluated. The determination of ultimate resolution was, of course, outside the present scope of work. Interest in the resolving power of the holocamera, however, led to a cursory evaluation of one of the cold flow test holograms. It was concluded from this very preliminary work that 25 micron resolution was possible.

6. RECOMMENDATIONS

The application of pulsed laser holography to the detection and recording of droplet dispersions within the confined atmosphere of a small rocket combustion chamber is planned for Phase II of the current program. The first step in demonstrating the feasibility of using holography techniques in the study of rocket combustion has been demonstrated. With the successful results obtained from the Phase I open flame test program providing a base of knowledge, it is strongly recommended that the Phase II test work be implemented.